DEVELOPMENT OF THE URBAN PASSENGER TRANSPORTATION LIFE CYCLE INVENTORY FOR COMPARISON ACROSS MODES MODEL (TRANSPORTLIFECAMM)

BY

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DISSERTATION

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Abstract

DEVELOPMENT OF THE URBAN PASSENGER TRANSPORTATION LIFE CYCLE INVENTORY FOR COMPARISON ACROSS MODES MODEL (TRANSPORTLIFECAMM)

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Against the backdrop of the increasingly complex urban passenger transportation challenges associated with megacities during the 21st century, and the effort to find the most sustainable modes of transportation for them, the spreadsheet-based model TransportLifeCAMM was developed. This model allows users in the US and Mexico to compare life cycle environmental impacts from automobile, bus, and/or subway. While other models to estimate environmental burdens from transportation exist, few of them consider emissions or energy consumption over the entire life cycle of the vehicle and the fuel (including vehicle manufacture, fuel production, maintenance, and end-of-life disposal). Furthermore, even fewer of the available models consider the infrastructure contribution to the transportation mode, and none to the level of granularity offered by TransportLifeCAMM. If the goal is to discover which is the most sustainable transportation mode, all life cycle phases for the vehicle, energy and infrastructure subsystems should be considered.

The overall goal of this study was thus to develop a comprehensive life cycle assessment (LCA) spreadsheet model that compares environmental impacts of three transportation modes - subway, bus,

and automobile – and their associated infrastructure, over their entire life cycle. Specific objectives were:

1. To develop a spreadsheet model for comparing life cycle impact of three transportation modes (subway, diesel bus in a Bus Rapid Transit context, and automobile), using traditional comparison criteria,

2. To apply the model to Mexico City as a case study,

3. To add an exergetic life cycle assessment to the spreadsheet model, and apply it to the case study of Mexico City as well,

4. To identify a range of impacts for the case study due to sensitivity in model inputs.

The main contribution of this study was the development of a robust LCA-based methodology to evaluate and compare the environmental impacts of three transportation modes, applicable to any major city in North America. Furthermore, this methodology provided the basis and framework for TransportLifeCAMM, a freely-available, spreadsheet-based model. Since running Simapro or any other LCA software is time-consuming and complex, and requires considerable training and time to collect input data for hundreds of parameters, the user-friendly TransportLifeCAMM, based on Simapro output, allows anyone with basic spreadsheet knowledge to estimate emissions, with only a few readily-available input parameters. TransportLifeCAMM provides the measurement and analysis of environmental impacts for greenhouse gases (GHG), criteria air pollutants (CAP), cumulative energy demand and cumulative exergy demand throughout the life-cycle of each vehicle, and in units of grams of impact/passenger-kilometer. Additionally, it must be noted that no other scientific analysis or environmental/transportation study in Mexico City had been performed within an LCA framework previously to this work.

Moreover, few other transportation LCA studies include the system's infrastructure, and none to the level of granularity provided by TransportLifeCAMM. Further contributions of this research are that no LCA study has been performed across these three transportation modes in any city, and that no other LCA-based model offers an exergy analysis for transportation modes.

For the LCA simulations, the Simapro version 8.3.2 software was used, and the NIST's BEES+ method was used to conduct the main environmental impact assessment portion of the LCAs, which was supplemented by the Cumulative Energy Demand and Cumulative Exergy Demand methods for all three transportation modes. Data sources included published scientific papers and journals, governmental reports and statistics, both for the United States and for Mexico, theses and dissertations, environmental product declarations, technical specifications from the vehicles' manufacturers, transit authority reports, public information requests, USLCI database records for the onroad vehicles, as well as Ecoinvent and other databases contained in Simapro, trade journals, engineering reference books and textbooks, industry websites, technical and operational manuals, particularly for the bus and the subway, and as of yet unpublished data from the 2017 Origin-Destination survey in Mexico City.

Regarding the results of the LCAs applied to the case study of Mexico City, for the diesel bus (in the BRT system), it was found that the vehicle (bus) subsystem was the greatest contributor to the inventory for all criteria pollutants and greenhouse gases. Furthermore, it was also always the greatest contributor to the impacts, when evaluated by all impact assessment methods (BEES+, Traci, Impact 2002+, CED and CExD).

For the private car, the vehicle subsystem was also the greatest contributor to both the inventory and the impacts. As expected, the car was the most environmentally burdensome system. Results also ratified previous claims of the importance of including the infrastructure for a true LCA-oriented perspective of the system under study.

The main conclusion for the subway system is the acceptance of the initial hypothesis, and the rejection of the null hypothesis: the subway does represent the least environmentally burdensome transportation alternative, among the three modes studied herein. Moreover, for the subway, it was confirmed how dependent its environmental profile (i.e., its final output) is to the composition of the electricity mix. Additionally, it was found that emissions from the subway are almost entirely dependent on the electricity used for its operation, with much less significant contributions from the infrastructure subsystem than for the onroad modes.

In a three-way sensitivity analysis among the three transportation modes that evaluated both environmental impacts (with the BEES+ method), the Cumulative Energy Demand and the Cumulative Exergy Demand, it was confirmed that the heavy metro or subway has the least environmental impact and energy consumption, in a per passenger-kilometer basis. This is mostly the result of an increased ridership, with the subway's trains ability to transport a number of passengers, over their lifetime, that is at least two orders of magnitude above that of buses and cars. One of the findings of this research is that the increased lifetime performance, i.e., the greater number of kilometers travelled by each vehicle (car, bus, train) over their respective lifetimes, is also one of the factors that contributes to the subway's lesser environmental impact over the other two transportation modes analyzed herein.

In a two-way sensitivity analysis between the two mass transit modes, the bus and the subway, the low ridership case for the subway (918 passengers) was compared against both cases of “peak” buses for the BRT: the articulated bus carrying 160 passengers, and the bi-articulated bus with 240 passengers. Results showed that while the subway maintained its environmental advantage, in impacts measured in a per passenger-kilometer basis, over the articulated bus, it did not do so when compared to the bi-articulated bus, which performed marginally better than the subway. This result confirms the sensitivity of this methodology and of all transportation modes to ridership, and suggests that when planning a public transportation option, it behooves policy makers to strive to have the best available data on ridership, so as to make the best possible decision regarding on which transportation mode to invest, or to encourage.

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List of Abbreviations

BEES+	Building for Environmental and Economic Sustainability
BRT	Bus Rapid Transit
CED	Cumulative Energy Demand
CExD	Cumulative Exergy Demand
CNG	Compressed Natural Gas
EIA	Environmental Impact Assessment
EPD	Environmental Product Declaration
GHG	Greenhouse Gas or Gases
GIS	Geographic Information Systems
GLO	Global
GWP	Global Warming Potential
IMPACT 2002+	Impact Assessment of Chemical Toxics 2002+
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule

NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NREL/RNA	North American region
PKT	Passenger-Kilometer Travelled
PTW	Pump-to-Wheel
ROW	Rest of the World region
SETAC	Society of Environmental Toxicology and Chemistry
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TransportLifeCAMM	Urban Passenger Transportation Life Cycle Inventory for Comparison Across Modes Model
USEPA	United States Environmental Protection Agency
USLCI	United States Life Cycle Inventory Database
VKT	Vehicle-Kilometer Travelled
WTW	Well-to-Wheel
WTP	Well-to-Pump

Chapter 1

INTRODUCTION

1.1 Background

One of the major environmental challenges of the 21st century will be promoting sustainable development in megacities. In most cities worldwide, transportation sources are major contributors to air pollution, greenhouse gases, and energy consumption. Sustainable modes of transportation will therefore play a critical role in making it possible for twenty-first century cities to offer a high quality, sustainable form of life.

The transport sector, comprised of the road, air, rail, and water transport subsectors, is the largest and fastest-growing sector in Mexico in terms of energy consumption and greenhouse gas emissions. It produces approximately 18 percent of total greenhouse gas emissions in Mexico, with the road transport subsector accounting for close to 90 percent of the total energy consumption and CO_2e emissions from this sector alone (SEMARNAT, 2007). Between 1973 and 2006, energy use by road transport increased more than fourfold (IEA, 2008). In the decade from 1996 to 2006, Mexico's vehicle fleet nearly tripled, from 8.3 million vehicles to 21.5 million vehicles.

It is projected that over the next 12 years, Mexico's motorization rate –defined as the number of vehicles per 1,000 people—will continue to increase, following a worldwide trend. This means that while in 1960 Mexico had a motorization rate of approximately 25 vehicles, and in 2002 of approximately 200 vehicles, it is expected that by 2030 the motorization rate will be close to 750 vehicles per 1,000 people. (Dargay, Gately and Sommer, 2007). Consequently, it becomes imperative that alternative, more sustainable, urban passenger modes of transportation become available.

Determining which mode of transportation is most sustainable, however, is more complex than it may initially appear. An electric subway may produce no emissions from the subway car itself; however, if the electricity is produced via combustion of fossil fuels, emissions are simply transferred to the power plant. To determine which mode of transportation is more sustainable, a life cycle assessment approach must be used, which considers environmental impacts comprehensively from cradle to grave.

Life-Cycle Assessment (LCA) was formally organized as a systematic methodology in 1997, as part of an effort to globally assess the environmental impacts of products and services. LCA considers all stages of a product, process or service's life cycle, from the extraction of raw materials to production and consumption until their final disposal, considering also all the involved vectors (air, water, earth); this has led to this methodology being known as the "cradle-to-grave analysis." Thus, LCA has become a significant tool for environmental management, a central instrument in the assessment of environmental impacts, and a key support in decision-making for environmentally responsible options.

The data-collection effort in an LCA study, the second step, is known as the Inventory or Life Cycle Inventory (LCI). At this point, a model is made to include a product's environmental inputs and outputs. According to ISO 14040, this is the stage of a life cycle assessment that involves the compilation and quantification of inputs and outputs for a given product system throughout its life cycle.

The third step of the LCA deals with understanding the environmental relevance of all inputs and outputs, the listing of which is assumed to have been completed previously, in the second step. Therefore, the third step measures the environmental impacts of all the components and is referred to as the life cycle impact assessment, or LCIA. Thus, Life Cycle Impact Assessment (LCIA) is the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (ISO 14040).

It is important to note that, according to ISO, every LCA must at least include classification and characterization as the two obligatory elements of the Life Cycle Impact Assessment (LCIA). If these steps are not included, one may only refer to the study as a life cycle inventory (LCI). The inventory result is a list of the emissions to different media: air, water and soil, as well as the extractions to and from the system, which can cover hundreds of substances. While this makes the interpretation of the inventory result difficult, its advantage lies in the fact that it is not affected by the uncertainties introduced at the impact assessment stage of the LCA.

Several models are available for conducting inventories of emissions and energy consumption for passenger transportation (non-freight):

- US EPA's MOVES estimates tailpipe and evaporative emissions and energy consumption from on-road vehicles,
- The Fuel and Emissions Calculator (FEC) developed by Georgia Tech allows the user to compare costs, energy consumption, greenhouse gas emissions, and traditional air pollutants from buses, vans, and rail for a variety of different fuels. An expansion to passenger cars is under development.

Neither of the above models, however, uses a life-cycle approach: they simply estimate emissions during vehicle operation, but do not consider emissions or energy consumption over the entire life vehicle and fuel cycle (including vehicle manufacture, fuel production, maintenance, and end-of-life disposal). ***This is a serious drawback, if the goal is determining the most sustainable transportation mode***. Limiting consideration to vehicle operation only means that the transportation mode that is the most sustainable overall (considering all phases of the life cycle) may not be chosen.

Several additional models do take a life cycle approach. Each, however, has its own limitations:

- The GREET model developed by Argonne National Lab considers life cycle emissions from automobiles and light trucks, but does not evaluate other transportation modes.
- Mobitool, a Swiss tool developed by joint commitment of the ownership of SBB, Swisscom, Swiss Energy, Federal Office for the Environment and Öbu, compares vehicles which meet European emission and energy efficiency standards, but does not apply to US vehicles. Furthermore, Mobitool does not measure health impacts, but only offers information on the following selected indicators: CO_2 equivalents, primary non-renewable energy, particulate matter, both PM_{10} and $PM_{2.5}$, Non-Methane Volatile Organic Compounds, nitrogen oxides and recently, the "Unité de charge écologique 13" (UCE'13), or ecological load unit. Also, it does not include infrastructure.

Hence, there is a critical need for an environmental inventory and impacts model which compares transportation modes over their entire life cycle for the US, including infrastructure, vehicles, and fuel. This research aims to fill that gap.

In addition, none of the existing models mentioned above includes an exergetic analysis. Comparing life cycle energy consumption of different transportation alternatives tells how much energy is used (according to 1st Law of Thermodynamics); it does not tell the extent to which the alternatives degrade energy so that it is no longer usable or available for doing work (according to 2nd Law of Thermodynamics). Exergetic LCA thus provides an additional useful criterion for selection among alternatives.

The goal of this research is to develop a life cycle model for comparing transportation modes which includes exergy, traditional comparison criteria (energy consumption, greenhouse gas emissions, and emissions of traditional air pollutants), as well as environmental impacts. As an example or case study, the new model was applied to the assessment of three transportation modes in Mexico City: bus rapid transit, subway and private automobile.

The methodology proposed herein rests upon the intersection of several disciplines such as thermodynamics, through the concept and application of exergy as a criteria to assess energetic efficiency with LCA; Chemical Engineering, with an emphasis on material and energy balances; and Environmental Engineering considerations through the accounting of the effects on Air Quality of Greenhouse Gas Emissions (GHG), criteria air pollutants and environmental impacts resulting from the analysis of these three transportation modes in Mexico City.

1.2 Goals, Objectives and Expected Contribution of the Study

The overall goal of this study is to develop a life cycle impact model for comparing transportation modes which includes exergy.

Specific objectives are:

1. To develop a spreadsheet life cycle impact model for comparing 3 transportation modes (subway, diesel bus in a Bus Rapid Transit context, and automobile), which includes an exergy as well as traditional comparison criteria,

2. To apply the model to Mexico City as a case study,

3. To compare the traditional life cycle assessment results to the exergy results for Mexico City, and identify reasons for any differences,

4. To identify a range of impacts for the case study due to sensitivity in model inputs.

The scientific contribution of this work is that it develops a North American model for conducting an environmental impact assessment for various transportation modes, which includes all phases of the vehicle/fuel life cycle. In addition, the model includes an exergy comparison, which is not currently included in any transportation model.

The practical contribution is that it will provide an LCA for three modes (subway, bus, and automobile) which have not been compared before, and for Mexico City specifically. It is expected that the results of this study will provide a better framework, based on engineering principles, for governmental officers to better decide which transportation alternative should be encouraged in Mexico City.

1.3 Dissertation Organization

The remainder of this dissertation is organized as follows: Chapter 2 contains a bibliographic review of Life Cycle Assessment, of exergy and the exergetic method, of previous studies applying LCA in transportation, and of air quality and transportation in Mexico City. Chapter 3 describes the methodology and LCA framework employed in this research, as well as the data collection process. Chapter 4 presents the results and analysis of the research, and Chapter 5 summarizes the conclusions and offers recommendations for future studies in this area.

Chapter 2

LITERATURE REVIEW

2.1 Life-Cycle Assessment

The depletion of resources and pollution of the environment can be studied at the level of single processes or activities, but also at the higher level of networks of processes. At this higher systems level, ways to connect the consumption of products to as many aspects as possible of their industrial manufacturing and eventual disposition are investigated. Life-cycle assessment (LCA) has been called an analytical tool of chain analysis (Udo de Haes, 2007), that along with other similar tools such as environmental input-output analysis (env-IOA) and material flow analysis (MFA) seek to support the decision-making process.

LCA is a fundamentally quantitative tool that measures the potential environmental impacts of a product or service throughout its full life cycle, the “cradle-to-grave” approach. This allows for fair comparisons to be made between different products or services which fulfill the same function, with respect to their environmental burdens. This approach then includes the potential problems of a product that could be quite harmless in its use phase, while involving toxic emissions during its production or waste management; an example of such a product is PVC. Additionally, LCA can contribute to the design of an environmentally friendly product (Udo de Haes and Reinout, 2007).

LCA originated simultaneously in the UK, Switzerland, Sweden and the USA in the early 1970s. Its first objects of analysis were household products such as baby diapers, beverage containers and detergents, often with counterintuitive results. However, due to the methodological basis at that time being chaotic, individual LCA studies would frequently produce rather conflicting results.

In 1989 the Society of Environmental Toxicology and Chemistry (SETAC; http://www.setac.org) offered a home to LCA, as a result of which a consistent terminology was established. The first methodological aspect was the definition of a functional unit, i.e., a unit of function to which impacts are attributed. The reason for establishing a functional unit lies in the comparability of products. The second methodological aspect was the emphasis placed upon the adequate definition of a boundary for a system, product or service, from the onset of the study, and for this boundary to remain fixed throughout the analysis. A noteworthy disagreement, which eventually led to the formation of different schools of LCA, some focusing on material characteristics of the processes and others on their economic value, concerned the methodological problem of "allocation of multiple processes," a problem that arises from the fact that there are processes, known as multiple processes, which can fulfill more than one function. Examples of these processes are waste incineration combined with electricity generation, where the question is to what extent should the emissions be allocated to waste management, and to what extent to the production of electricity?

An important development became known as "life-cycle impact assessment," where the different emissions were attributed to a number of impact categories. Within each category, the different substances were added up using the "characterization factors," such as the global-warming potentials, the ozone-depletion potentials, and developed later, the factors for acidification, eutrophication, photochemical oxygen creation, and toxic substances.

In 1994, the International Organization for Standardization (ISO, http://ww.iso.org) started its 14040 series on LCA. To date, there are four standards (ISO, 2006) and several technical reports, which have resulted in a greater coherence in the methodology and practice of LCA. ISO standards are characterized by their normative language, i.e., "shall," "should" and "may." Something that shall be done is required in order to meet the standard; something that should be done must deserve a real attempt to be accomplished; something that may be done is optional for the practitioner.

With the advent of the ISO standards, a technical framework was established, attempting to separate as much as possible subjective and objective elements in the LCA process. This framework starts with the subjective phase, the “goal and scope definition” phase, in which the following elements are defined:

a) The product(s) or service(s) to be investigated
b) The desired level of detail of the study
c) The types of impact to be analyzed
d) The intended application of the results

Two objective phases follow, the life cycle inventory analysis (or LCI), which analyzes the processes of the product or service system in terms of their extractions and emissions, and the phase of life cycle impact assessment (or LCIA), assessing the environmental impacts thereof. These are followed by a fourth, again more subjective phase, the life cycle interpretation, in which the results are compared with the aims of the study. In case of non-attainment of the goals, further study or adjustment of the original aims can be undertaken. These four phases of an LCA are illustrated in Figure 2-1.

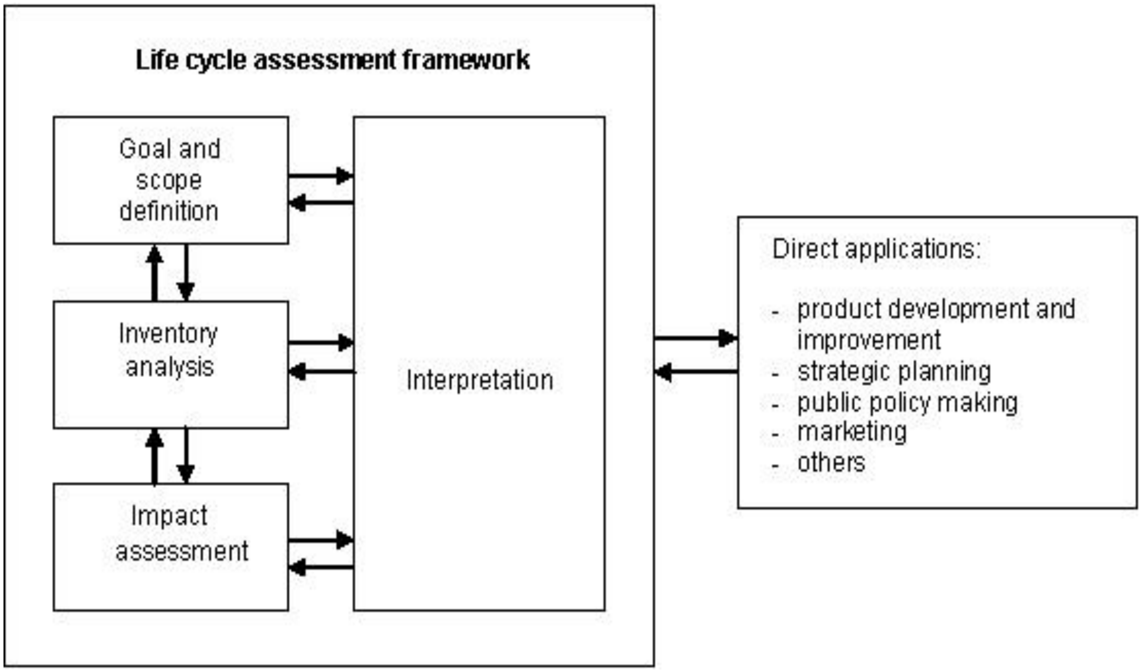

Figure 2-1. Four phases of Life-Cycle Assessment.

Source: ISO 14040.

2.1.1 Standards for LCA

The leading standards for LCA are:

- ISO 14040 Principles and Framework
- ISO 14044 Requirements and Guidelines

It must be noted that unlike the 14000 standards, it is not possible to get an official accreditation stating that an LCA, LCA methodology or LCA software has been made according to the ISO standard. The onus falls on the practitioner to conform to the ISO standards or to deviate from them. However, the most important consequence of adhering to these standards is the need for careful documentation of the goal and scope and of any possible interpretation issues. A second consequence of adhering to the ISO standards is that in some cases, a peer review by independent experts is mandated.

2.1.2 Single Issue Standards

More recently, single issue approaches that also take a life cycle perspective but focus only on one impact category, instead of multiple environmental issues, have been developed. These include carbon footprinting, for which there are two main standards: GHG Protocol and the draft ISO 14067, and water footprinting for which the draft ISO 14046 is being developed.

2.1.3 Goal and Scope Definition

Understanding that the model created by the LCA will ineluctably simplify and distort reality, the goal and scope definition attempt to deal with this problem. The better the goal and the scope of the study are defined, the greater assurance there will be that it has been performed consistently.

Additionally, one of the strongest justifications for a thorough description at this stage is the effort to avoid one of the most common pitfalls when trying to implement an LCA, i.e., the lack of a clear purpose and intended application of the study.

2.1.3.1 Goal Definition

The ISO standards specify that the goal definition must:

- Describe unambiguously the application and intended audiences.
- Clearly describe the reasons for carrying out the study. (Is the practitioner or commissioner trying to prove something or just intending to provide information, etc.)
- Clearly describe the implications of the dual purpose, in case that the LCA study serve more than one purpose. If different versions (internal and external) of the study use different impact assessment methods, for example, the goal definition must state so.

2.1.3.2 Scope Definition

The scope of the study describes the most important methodological choices, assumptions and limitations. Since an LCA is an iterative process, the initial set of choices and requirements may be subsequently modified or adapted.

Among the most significant methodological choices we find the definition of the functional unit and reference flow, the initial system boundaries, the criteria for inclusion of inputs and outputs, and how to deal with multifunctional processes.

2.1.4 Functional Unit and Reference Flow

The functional unit is the comparison basis.

2.1.5 Initial System Boundaries

One of the most important considerations when identifying the boundaries is to determine whether the production and disposal of capital goods will be included. In this regard, three orders can be distinguished:

1. First order: only includes production of materials and transport; rarely used in LCA.
2. Second order: all processes during the life cycle are included but the capital goods are left out.
3. Third order: includes all processes and capital goods, although the latter are only modeled in a first order mode. That is, only the production of the materials needed to produce the capital goods are included.

Whereas capital goods are often not included in LCAs, in some cases they contribute up to 30% of the environmental impacts. In practice, the suggestion is to follow the principle to include capital goods only when they have a significant contribution to the environmental impact. For the purposes of this study, and since Chester, Horvath *et al* (Chester, 2009) have shown that total life-cycle energy inputs and greenhouse gas emissions contribute an additional 63% for roadway, 155% for rail and 31% for air systems over vehicle tailpipe operation, the decision was made to include capital goods, i.e., to conduct a third-order LCA.

There are a variety of databases and software, both for the LCI phase and for the LCIA phase which are largely compatible with ISO requirements. For the purposes of this dissertation, PRé Sustainability's SIMAPRO © was used.

2.1.6 Inventory

The most demanding and usually time-consuming stage in an LCA is data collection. In spite of the extensive amount of secondary data available in the databases, at least some materials or processes are bound to be unavailable, and consequently, data collection for them must then be overtaken by the practitioner. A distinction between two types of data is made:

1. Foreground data. It describes a particular product or function, and is data that needs to be acquired specifically for the system under study.
2. Background data. It can be found in databases and from literature, and is data for the production of generic materials, energy, transport and waste management.

Regarding background data, two of the most important data sources available to the LCA community are the Ecoinvent database and input-output databases.

2.1.6.1 The Ecoinvent database

The Ecoinvent database v.3.0 covers over 10,000 processes. It is jointly created by different Swiss institutions, such as ETH Zurich, PSI, EMPA, EPF Lausanne and ART, who are responsible for data collection, along with an "Editorial Board" responsible for quality control. The Ecoinvent database is described at its website, www.ecoinvent.org.

The Ecoinvent database is probably the best documented database available for LCA studies, covering, most likely, the broadest range of data. Additionally, Ecoinvent has a consistent specification of uncertainty data (usually as a lognormal distribution with standard deviation), and particularly relevant for this study, Ecoinvent includes capital goods as a default, which is not only important for energy systems such as wind and hydropower, but also for transportation systems. As previously mentioned, the decision to include capital goods in this study, i.e. to conduct a third-order LCA, makes the inclusion of the Ecoinvent database a convenient choice for this purpose. Moreover, version 3.0 of the Ecoinvent database has a more international scope.

Within Simapro, there are four dataset versions implemented:

1. Allocation default, unit processes
2. Allocation default, system processes
3. Consequential, unit processes
4. Consequential, system processes

When the principles of attributional modeling have been applied, an allocation dataset is used, whereas a consequential dataset is used when the principles of consequential modelling have been applied. Furthermore, each process is divided in two versions: unit processes and system processes. The unit process version contains emissions and resource inputs from one step, plus references to input from other unit processes; when selected within Simapro, this version will automatically include all upstream processes. The system version has no links to other processes, and offers no insight into the inputs and outputs of the separate supply chain in the production system. Therefore, this version has therefore been likened to a “black box”. The unit process version contains uncertainty information, although it offers a relatively slow calculation. The system process version has a fast calculation but no uncertainty information. Generally, unit processes will be used in full LCAs while system processes will be used in LCA screenings.

2.1.6.2 Input output databases

Input output databases contain data per economic sector rather than per process, as conventional databases do. Their advantage is the ability to have an assessment for an entire economy; their disadvantage is that the result may not be specific enough for the research questions.

Input output databases describe an economy in a table as financial exchanges of supplies between sectors, or to consumers, or for export. This type of databases is applied within an LCA to divide all environmental data by the added value (the difference between total value and total cost or purchases) of each economic sector. Thus, the input output table traces all environmental loads throughout the whole economy. As such, there are no system boundary problems, “everything” is included in the system and all allocations are based on economic value. Consequently, when using input output (IO) tables, mass or energy are no longer used as inputs, but only economic value.

2.1.7 Impact Assessment

Frequently, the LCA practitioner does not develop and impact assessment methodology, but rather only chooses one that is already included in the available LCA software. For the election both of the method and the impact categories, the Goal and Scope definition of the study remains –as with the Inventory stage—the main source of guidance.

Since the choice of the impact assessment method depends largely on the audience addressed, it is important to decide beforehand up to what level of integration the results are required. That is, depending on how the results will be reported, and to whom, the impact assessment methodology and categories are chosen.

Once the impact assessment method has been chosen, it is standard practice to follow it, instead of selecting individual impact categories. Only in rare instances is there any need to modify these methods, or to create a completely new one.

Since the ISO 14040/44 standard defines an LCA as a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its life cycle, it is clear that impact assessment plays an integral part in an LCA.

Life cycle impact assessment is defined as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. ISO 14040/44 makes a distinction between:

- Obligatory elements: classification and characterization
- Optional elements: normalization, ranking, grouping and weighting

Figure 2-2 presents both the impact categories that have been proposed by UNEP/SETAC, and the difference between midpoint category methods, which stop the environmental assessment at the level of environmental problems, and those based on endpoint categories, which measure impacts all the way to environmental damages.

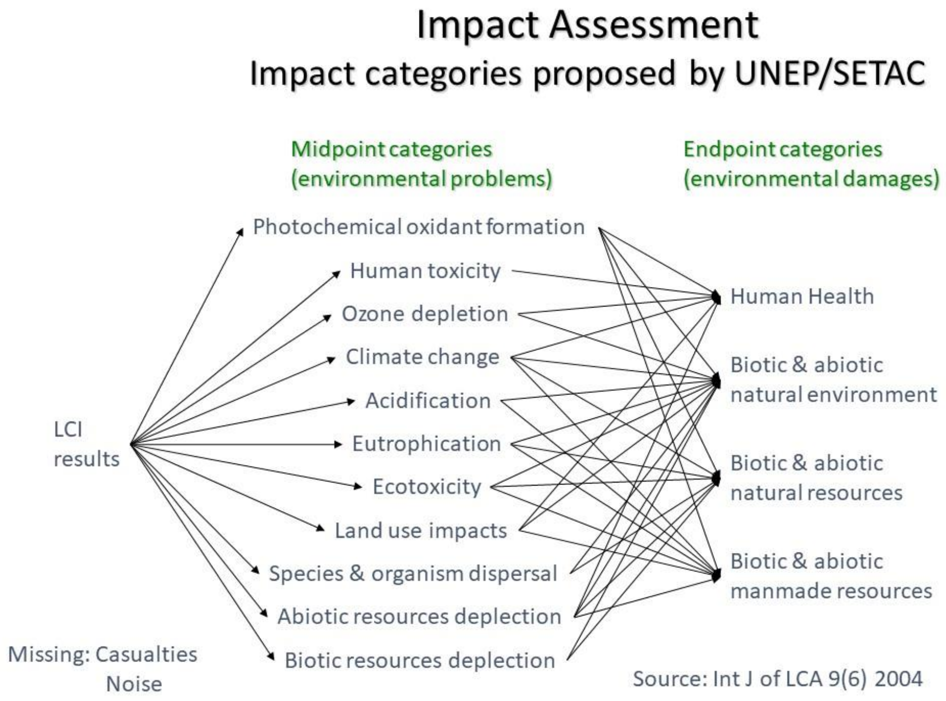

Figure 2-2. Impact Categories Proposed by SETAC. (Source: International Journal of LCA 9(6) 2004).

2.1.8 Interpretation

According to ISO 14044, the fourth and last step of an LCA, Interpretation, is a checklist to test whether conclusions are adequately supported by the data and the methodology employed.

2.1.9 Limitations of LCA

LCA has several important limitations. The first problem is the definition of the system boundary, determining at which level processes are to be included, since there is always a process behind a process. Generally, LCA stops before the capital goods (for example, before the production of trucks used for transportation of collected glass, but including the fuel they consume to carry out the collection and disposal of the glass), but this is arbitrary and the relevance of the not-included processes is unknown.

Other limitations of LCA are the spatial and temporal resolutions; analysis is typically performed without any spatial differentiation –i.e., the analysis treats processes in the same way at different companies or locales—and with a steady-state character. This also implies that the only impacts considered in LCA occur within a regular timeframe, and that potential catastrophes are not included. Thus, LCA is not suitable for a precautionary approach (Udo de Haes, 2007). Additionally, LCA is developed for impacts with an input-output character, such as extractions from the environment and emissions to it, which are both well-linked to a functional unit. However, LCA cannot easily account for impacts related to land use, nor does it consider social and economic impacts.

In the design of technology with as low an environmental burden as possible, emphasis is shifting from emission control to a critical analysis of resource consumption. The traditional end-of-pipe approach and abatement techniques are being increasingly complemented with process adjustments and input choices. Engineers are now interested not only in reducing greenhouse gas emissions and local pollution but also in decreasing the depletion of resources and in improving the security of supply for processes. Therefore, over recent years there has been a growing interest in finding a suitable methodology to account for resource consumption in LCA, which has been historically focused on emissions.

There are other methodologies for environmental impact assessment, such as the Strategic Environmental Assessment (SEA). This methodology is applied mostly in the 27 countries of the European Union. The SEA is a means to integrate policies, plans and programs (PPP) and as such is considered, by the European Union, of higher order than a Life Cycle Assessment, mostly from the viewpoint of public policies. In order to conduct a SEA, there is no international agreement nor standard, i.e. an ISO standard, unlike what is true for an LCA study. Additionally, there is no authority directly responsible for enforcing the results of a SEA.

2.2 Exergy and the Exergetic Method

Under the assumption that emissions have been effectively controlled, industrial processes are then governed by two boundary conditions: economics and thermodynamics (Whitesides, 2005). Thermodynamics, unlike economics, has the ability to assess both process efficiency and resource inputs. As a result of this, the suggestion has been made by several authors (Cornelissen, 2002; Finnveden, 1997; Ayres, 1998; Dincer, 2013) to apply thermodynamics, and more specifically, exergy accounting, to resource consumption in life cycle assessments.

Exergetic Life-Cycle Assessment (ExLCA) has been applied to the study of different materials that could substitute disposable polyethylene grocery bags. In this case, cotton, Kraft paper, polypropylene, high-density and low-density polyethylene (obtained both from raw oil and from natural gas) as well as these same polyethylenes with a degradation-inducing additive were analyzed (Ramírez-Rayle, 2010). Another instance where a full ExLCA has been applied was the analysis of polyethylene terephthalate (PET) bottles versus glass and aluminum bottles, as well as their recycled products, in order to determine the best alternative among them, from the environmental and sustainability viewpoint (Alegría-Mejía, 2011). Exergy accounting had its origin in production analysis, in terms of efficiency (Kotas, 1985, 2012) and resource accounting (Szargut, 1988).

Exergy is a thermodynamic function derived from the Second Law of Thermodynamics. Exergy is defined as the maximum work that can be harnessed from the use of resources. It can also be defined theoretically as the minimal work necessary to produce a material with its specified state in a reversible way from common materials in the environment. It evaluates to what extent a resource stands out from its environment from a physical/chemical point of view. Local environmental conditions can be defined for processes of regional impact. For industrial processes such as are typically considered in LCA, global conditions of 1 standard atmosphere (101325 Pa) and 298.15 K, together with average geophysical chemical characteristics, are assumed.

It must be noted that the effort to integrate energy and exergy analyses into LCA is not without its critics (Udo de Haes, 2007), who point out the possibility of these two types of analyses continuing to exist as distinct members of a coherent family of tools for chain analysis.

The capacity of natural resources to undergo thermal, chemical and biological processes is fundamentally associated with the deviation from their original state and composition relative to the state and composition of the environment. Thus, the measurement of the maximum work that can be obtained in environmental conditions can be accepted as a measurement for the assessment of the exploitation of natural resources. This quantity has been named exergy (Szargut, 2005). Exergy is the property of the system which gives the maximum power that can be diverted from the system, when it is brought to a thermodynamic equilibrium state from a reference state (Koroneos, 2003).

The decrease in exergy throughout the total life cycle of a product allows for the evaluation of the degree of thermodynamic perfection of the production processes involved, which leads to the analysis of the production routes for that service or product, with the intent of identifying the routes and processes with the best thermodynamic performance.

Exergy analysis is a useful tool to know to what degree energy is wasted. This type of analysis is carried out in an attempt to identify those points that can be modified to achieve an increase in production while simultaneously diminishing energy losses. This technique is used to assess the performance of production chains, industrial processes and equipment or services and is based on the simultaneous application of the two fundamental laws of thermodynamics: conservation of energy and degradation of energy. Synonyms that have been used for exergetic analyses include “exergo-ecological analysis,” “exergo-economic analysis” and “analysis of thermodynamic availability.”

The origins of exergy can be found first in the statement of the second law of thermodynamics, which is due to the work of Carnot and Clausius (García-Aranda, 2003). Afterwards, the first contributions in the field of exergetic analysis can be found in the works of G. Gouy, A. Stodola, J.W. Gibbs and F. Bosnjakovic (Santoyo-Hernández, 2006).

In 1875, in a paper entitled “On the equilibrium of heterogeneous substances,” Gibbs identified the theoretical foundations of the concept of exergy, which he called “Available Energy of the Body and Medium.” Gibbs also introduced the concept of the maximum work of chemical reactions, known as Gibbs energy (ΔG) or free energy or Gibbs free energy (Santoyo-Hernández, 2006). Several years after this, G. Gouy in France and A. Stodola in Germany would formulate, apparently independently, a law that estimates the loss in the capacity of a system to produce work because of thermodynamic irreversibility (DeBaufre, 1925). This law did not create much interest at first. The first published papers based on this law were made by Jouget (1907), Darrieus (1930) and Keenan (1932).

Gouy proposed in 1889 the use of a new thermodynamic function to generalize the fact that only a fraction of thermal energy can become mechanical energy, which he called “Energie Utilisable” (usable energy) (Szargut, 2005). Nine years after that, in 1898, Stodola used the term “freie technische Energie” to refer to the ability of a process to carry out work (Szargut, 2005). Different terms continued to appear. For instance, F. Bosnjakovic analyzed the impact of irreversibilities and was a proponent of the idea of devising ways to counteract them. In 1935 he published in Germany a book on thermodynamics, where he proposed the practical application of analyses based on the second law of thermodynamics, using the concept of “Technische Arbeitsfahigkeit” (technical working capacity) (Fratzscher, 2002).

An energy analysis, which is based on the first law of thermodynamics, provides a qualitative evaluation of the losses in the different components of the system. The exergy analysis, based on the second law of thermodynamics, provides a clearer view of the energy losses in the system, as it presents quantitative and qualitative evaluation of the different losses.

2.2.1 First and Second Law of Thermodynamics

Thermodynamics studies the transformation of the general conditions of the transformation of energy and the relationship between energy and matter. The general conditions under which these transformations can be observed are summarized in the first and second laws of thermodynamics. The first law of thermodynamics references the conservation of energy, while the second law relates to the quality of energy.

The first law of thermodynamics is also known as the principle of the conservation of energy. It states that energy can change through interactions from one form to another, but the amount of energy remains constant throughout all its transformations. This law establishes the existence of a state function called internal energy (U) such that a change in its value is given in a system in movement through the difference between heat (Q) and the work (W) performed by the system during a change in conditions.

$$\Delta U = Q - W \qquad \text{(Equation 2 - 1)}$$

Since the first law establishes that "energy is neither created nor destroyed; it is only transformed", the change in the total energy of a system during a process is the sum of the changes in its internal, kinetic and potential energies ($\Delta U, \Delta KE\ and\ \Delta PE$) respectively.

$$\Delta E = \Delta U + \Delta KE + \Delta PE \qquad \text{(Equation 2 - 2)}$$

Where:

$$\Delta U = m(u_2 - u_1) \qquad \text{(Equation 2 - 3)}$$

$$\Delta KE = \frac{1}{2}m(v_2^2 - v_1^2) \qquad \text{(Equation 2 - 4)}$$

$$\Delta PE = mg(z_2 - z_1) \qquad \text{(Equation 2 - 5)}$$

In a closed system, considering the changes in potential and kinetic energies when a change of state takes place as negligible, the energy that is transferred is basically of two types: heat (*Q*) and work (*W*). Using the notation where the work that enters into the system is positive and the work that exits the system is negative, we arrive once more at the statement of the first law of thermodynamics, Equation 1. In this equation, *U*, the internal energy represents the different types of energy contained in the system at an intermolecular and intramolecular levels, such as the energy associated with the molecular spin, molecular bond, magnetic bipolar momentum, molecular translation, molecular rotation, molecular vibration.

Heat and work refer to the flow of energy through the border of the system. These forms of energy are not stored; therefore, they are not characteristics of the system. Considering that the system operates under continuous flow and steady state, that is, that the conditions and velocities of flow in all points throughout the flow trajectory are constant relative to time, the first law of thermodynamics can be written as:

$$\Delta H = Q - W_u \qquad \text{(Equation 2 - 6)}$$

In Equation 6, W_u is all the transfer of work between the system and its surroundings except for the work of expansion-compression; ΔH is the change of enthalpy that takes place due to a process that operates under the aforementioned conditions.

In the most general case, for an open system operating under flow conditions where its properties are a function of time, and for a differential change of state, the variation of enthalpy relative to time for ideal gases or solutions is written by:

$$\frac{dH}{dt} = Q - \left\{ \sum_{k}^{n} \sum_{i}^{m} \dot{N}_{ik} \; H_{ik} \right\} - \dot{W}_u \qquad \text{(Equation 2 - 7)}$$

Where the sum from *k* to *n* represents the streams, while the sum from *i* to *m* represents the species in each stream, $\dot{N}_{ik}$ is the molar flow, $\dot{H}_{ik}$ is the molar enthalpy. Thus, $\dot{N}_{ik}$ is the molar flow of specie *i* in the stream *k*, while $\dot{H}_{ik}$ is the enthalpy of specie *i* in stream *k*. The sum is performed over all the inflow and outflow streams.

The first law of thermodynamics only affirms that an increase in one form of energy is accompanied by a decrease in some other form, but does not state any restriction on the types of conversions of energy that may occur; it does not distinguish between work and heat. There is a very important difference between work and heat that is not made apparent in the first Law: while in theory it would be possible to convert work completely into heat, in practice it is impossible to convert heat completely into work without modifying the surroundings.

2.2.2 Entropy and the Second Law of Thermodynamics

The concept of entropy was suggested for the first time by the German physicist Clausius, and was at first conceived only in the macroscopic sense. Afterwards, as the understanding of the microscopic nature of matter, as well as the application of statistical and quantum mechanics of the structure of matter came into being, a microscopic interpretation of entropy has offered new revelations.

Entropy is a quantitative measurement of the degradation that energy suffers as a result of changes in the universe. In a reversible change, the total entropy of the universe remains constant, while in an irreversible change the total entropy of the universe increases in direct proportion to the amount of mechanical energy that is degraded to thermal energy.

2.2.3 Second Law of Thermodynamics

In a spontaneous process, the ability of the universe to perform work decreases because whenever disorder is introduced somewhere or in something, thermal energy becomes less available to be converted into mechanical work. Therefore, the energy that is used for disorder will no longer be available to perform work. The state property that was defined to study this behavior was entropy (S).

If a system goes from state 1 to state 2, ΔU can be found by measuring Q and W from or to the system, and using the expression of the first law, $\Delta U = Q - W$. Similarly, the change of entropy while going from state 1 to state 2 is found by:

$$\Delta S_{system\ 1\rightarrow 2} = \int_{state\ 1}^{state\ 2} \frac{dQ_{rev}}{dT_{system}} \qquad \text{(Equation 2 - 8)}$$

Considering an open system that operates under unstable flow conditions, for a differential change, the second law of thermodynamics is written as:

$$\frac{dS}{dt} = \frac{\dot{Q}}{T} - \left\{\sum_{k}^{n}\sum_{i}^{m} N_{\imath k}\dot{S}_{\imath k}\right\} + \dot{S}_{GEN} \qquad \text{(Equation 2 - 9)}$$

Where $\dot{S_{GEN}}$ is the entropy generated due to the irreversibilities of the process and S_{ik} is the entropy of specie *i* in stream *k*.

The relationship between the useful energy that exits a converter relative to the energy that was input is always lower than one. Consequently, the use of any type of fuel means, of necessity, a degree of waste that can eventually become pollution if the ecosystem does not have the capacity to absorb it at the rate it is generated.

Among living beings, the most efficient plants capture through photosynthesis close to 2% of the energy received from the sun as light; herbivores barely make use of 10% of the plants' energy, and carnivores take advantage of only 10% of that amount of energy. Waste of energy, therefore, is natural; however, human beings have the possibility of directing their productive efforts and their consumption habits in a way that minimizes this natural tendency to the degradation of energy. Therefore, with the second law as a foundation, conditions can be established where the use of available energy resources can be both prudent and intelligent.

The postulation of the first two laws of thermodynamics was crystallized in 1824 when the French physicist Sadi Carnot described the results of his research on the energetic flow of the vapor machine.

Summarizing the first and second law of Thermodynamics, we can say that:

First Law of Thermodynamics: "Energy is conserved."

Second Law of Thermodynamics: "Energy is degraded."

Thus, in real processes, energy is not destroyed, but only transformed into other forms, each of these less apt to carry out further processes. This is why an additional concept must be introduced to characterize the quality of energy vis-à-vis other considerations; this concept is *exergy*.

2.2.4 Gibbs' Free Energy

The capacity of a spontaneous reaction to deliver useful work can be interpreted from the point of view of a fundamental property that is known as Gibbs' free energy:

$$G = H - TS \qquad \text{(Equation 2 - 10)}$$

The variation in the Gibbs' free energy of products and reactants in isothermal processes can be written as:

$$\Delta G_r = \Delta H_r - T\Delta S_r \qquad \text{(Equation 2 - 11)}$$

Where the subscript *r* denotes a chemical reaction.

The thermodynamic expression of the general variation in Gibbs' free energy for isothermal processes is:

$$\Delta G = \Delta H - T\Delta S \qquad \text{(Equation 2 - 12)}$$

For a reaction to be thermodynamically feasible, the change in Gibbs' free energy must be negative; that is, $\Delta G_p < 0$. Thus, any factor that reduces enthalpy or increases the entropy of particular species in the system will shift the reaction equilibrium in that direction.

From the viewpoint of exergy, a reference environment is defined as a large enough body or environment in a state of perfect thermodynamic equilibrium. In this conceptual environment, there are no gradients or differences in pressure, temperature, chemical potential, kinetic energy or potential energy; thus, there is no possibility to obtain work from any type of interaction between the different parts of the environment. Any system outside of this environment with one or more parameters such as pressure, temperature or chemical potential that are different from those of the environment contains potential work relative to the environment. The environment is, therefore, a natural reference medium to assess that potential work in different classes of systems. The importance of the reference environment lies in the fact that in the exergetic studies of a process it is necessary to know the exergy values of the intervening flows, which are dependent on the conditions of that reference environment.

The exergy transfer can be associated with heat interaction, mass flow, and work interaction (Cornelissen, 1997). The exergy associated with heat interaction is given by Equation 2 - 13:

$$\dot{E} = \int_A \left(\frac{T - T_0}{T} \right) \dot{Q}_i \, dA$$

(Equation 2 - 13)

Where *A* is the heat exchange surface, *T₀* is the ambient temperature, *T* is the temperature at which the heat transfer takes place and $\dot{Q}_i$ is the heat transfer rate.

The total work W' done by a system excludes flow work, and can be written as follows:

$$W' = W + W_x$$ (Equation 2 - 14)

Where *W* is the work done by a system due to change in its volume and W_x is the shaft work done by the system. The term “shaft work” includes all forms of work that can be used to raise a weight (i.e., mechanical work, electrical work, etc.) but excludes work done by a system due to change in its volume.

Equation 2 - 14 separates total work W' into two components: W_x and W. The exergy associated with shaft work Ex_W is by definition W_x.

The exergy transfer associated with work done by a system due to volume change is the net usable work due to the volume change, and is denoted by W_{NET}. Thus, for a process in time interval t_1 to t_2:

$$(W_{NET})_{1,2} = W_{1,2} - P_0(V_2 - V_1) \qquad \text{(Equation 2 - 15)}$$

Where $W_{1,2}$ is the work done by the system due to volume change $(V_2 - V_1)$. The term $P_0(V_2 - V_1)$ is the displacement work necessary to change the volume against the constant pressure P_0 exerted by the environment.

For the purposes of this dissertation, it is important to note that as for shaft work, the exergy associated with electricity is equal to the energy.

The exergy associated with mass flow is divided into chemical, physical and mixing energy. Chemical exergy is given by Equation 2 - 16:

$$Ex_{chem,i}^{0} = \sum_{j=1}^{n} v_j Ex_{chem,ref-j} - \Delta_r G_i^0 \qquad \text{(Equation 16)}$$

Where v_j is the specific volume of the *j*th component and $\Delta_r G_i^0$ is the reaction exergy so as to bring the component to the reference state and is equal to the standard Gibbs energy change. In the above equation, *n* is the number of components and *0* is the reference condition.

Additionally, chemical exergy has been defined elsewhere (Hinderink *et al*, 1996) as:

> *The chemical exergy of a material stream refers to that part of its total exergy that results from the difference in chemical potential—evaluated at reference conditions* (T_0, P_0)*—between the pure process components and the reference environment components in their environmental concentration.*

In practice, chemical exergy is often calculated using Gibbs energies of formation from an internally consistent databank, such as is often found in a flowsheeting simulator such as Aspen Plus ©, and from reference tables of chemical exergies.

Chemical exergy reflects the resource's deviation in chemical composition from the reference environment. For the majority of natural resources, this chemical exergy is the most important contribution to its exergetic value.

Physical exergy, which is defined as the work obtained when the working fluid is brought from the reference condition to the ambient condition, is given by Equation 2 - 17:

$$Ex_{phys} = \Delta_{actual-0}\left[F\left(\sum_{i=1}^{n} x_i H_i^F - T_0 \sum_{i=1}^{n} x_i S_i^F\right) + G\left(\sum_{i=1}^{n} x_i H_i^G - T_0 \sum_{i=1}^{n} x_i S_i^G\right)\right] \quad \text{(Equation 2 -17)}$$

Where *H* is the enthalpy, *S* is the entropy and *x* the molar ratio of the *i*th component. Additionally, *F* refers to the liquid phase whereas *G* refers to the vapor phase, as changes in composition may occur.

Physical exergy has also been defined as (Hinterik, 1996):

The physical exergy of a material stream is the maximum obtainable amount of shaft work (or electrical energy) when this energy is brought from actual conditions (T, P) to thermomechanical equilibrium at ambient temperature (T_0, P_0) by reversible processes and heat being exchanged only with the environment at T_0.

Finally, mixing exergy, which always has a negative value, may be calculated using algorithms for the mixing enthalpy and entropy:

$$Ex_{mix} = \Delta_{mix} H - T_0 \Delta_{mix} S \qquad \text{(Equation 2 - 18)}$$

The total amount of exergy transfer associated with mass flow is thus calculated by the equation:

$$\underset{total}{\dot{Ex}} = \dot{m}\left[Ex_{chem} + Ex_{phys} + \Delta_{mix} Ex\right] \qquad \text{(Equation 2 - 19)}$$

where $\dot{m}$ is the mass flow.

2.2.5 Irreversibility

The concept of irreversibility provides a solid parameter with which to gauge the depletion of natural resources throughout the life cycle of a product or process. Exergy flows are assessed within the framework of the LCA and the destruction of exergy, i.e., the irreversibility of a process is calculated, in an effort to reduce it as a way to improve the efficiency and efficacy of processes and systems.

Irreversibilities then allow for the calculation of the amount of exergy losses of production and other type of processes involved in any given system (Cornelissen, 1997).

Irreversibilities are probably easier to conceptualize as the energy that has not been taken advantage of, or utilized, in a thermodynamic process.

Considering Kotas and Szargut, and the above definition of exergy as the maximum potential work that can be obtained from a material or a form of energy in relation to its environment, it can be seen that theoretically, potential work could be obtained from reversible processes. In practice, however, there are only irreversible processes. The system of reference (“the environment”) is significantly larger than any system being studied, which means that its parameters do not affect the system under consideration. For practical purposes, the system’s temperature is set at 298.15 ˚K (T_0) and its pressure at 1 atmosphere (P_0).

Irreversibility, also known as the loss or destruction of exergy, is calculated by performing a balance and taking the difference between the input exergy flows and all the output exergy flows, that is:

$$I = \sum_{input} E_i - \sum_{output} E_j \qquad \text{(Equation 2 - 20)}$$

Another way of calculating irreversibilities is given by the Gouy-Stodola equation, where the increase in entropy is multiplied by the temperature of the environment:

$$I = T_0 \left[\sum_{output} S_j - \sum_{imput} S_i \right] = T_0 \Delta S \qquad \text{(Equation 2 - 21)}$$

2.2.6 Comparing Exergy versus Emergy

To address the suitability of exergy as an indicator of the energetic sustainability in this study, it will be compared herein to emergy and other approaches that have been proposed for a global energy sustainability indicator.

Exergy is a thermodynamic property that links the first and the second thermodynamic principles, as discussed above. It also connects the system under study with the environment where it is found. Since the first law of thermodynamics measures quantity of energy and the second measures irreversibilities, i.e. the *quality* of the energy, exergy provides a single thermodynamic indicator which is able to deal with both issues simultaneously, which is convenient for energy sustainability assessments. Furthermore, from a conceptual standpoint, the most important consequence of the introduction of exergy is the realization that the amount of useful work that can be extracted from a certain system is not measured by the variation of its enthalpic content, because in any process a portion of that energy is devalued by the unavoidable irreversible entropic generation (Sciubba, 2010, p. 3698). The consideration of both the first and second laws of thermodynamics in the Exergetic Analysis procedure leads to an "internally coherent and methodologically correct procedure of analysis" (*ibid*, p. 3699).

"Emergy, spelled with an m, is a universal measure of real wealth of the work of nature and society made on a common basis. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use" (Odum, Brown, 2000). In essence, Emergy Analysts compute the emergy content of a commodity in terms of the Joules of solar energy that went into its "production," where the term "production" is here meant in an extended sense, to indicate both anthropic and natural processes. To differentiate between different "qualities" of this "pristine form of energy," Odum coined the term Solar Emjoule (sej, measured in Joules). Emergy attempts, as exergy, to account for the quality of energy, but it does so by the use of a transformity factor. The transformity factors for calculation of emergy are found from the network as the number of solar equivalents that it has cost to construct the considered organism or commodity.

It can be seen that this emergy concept is based on the idea that something is valuable "according to what was invested into making it: the higher the required investment, the higher the quality assigned to the item." (Sciubba, *op. cit*. p. 3700). As such, emergy is attempting to measure the environmental work required to generate ecosystem goods and services used by humans (Raugei and Rugani, 2014).

Since the Emergy Synthesis method has been criticized for its low accuracy and lack of standardization in the accounting procedure, it has been suggested that the inventory modelling principles behind the Life Cycle Assessment (LCA) method may improve it (*ibid*). While LCA draws the boundary around the life cycle of the system under study, Emergy Synthesis looks at a system as embedded in the larger natural system that underpins it, including all indirect and direct inputs over much larger time and space scales (*ibid*). Even the proponents of the integration between emergy and LCA view emergy as a valuable complement, rather than an alternative, to existing evaluation metrics (*ibid*).

A possible source of confusion between exergy and emergy analyses has been the use of the term "available energy" by emergy analysts. However, an extensive review of the original sources has demonstrated that the term "available energy" as coined by Odum meant for him "energy that can be used" rather than "exergy" (Sciubba, *op. cit*., p. 3705). The current consensus seems to be that Emergy Analysis is a legitimate energy method, but that Emergy and Exergy analyses ought to be carefully separated, as they use different methods, have a different metric and provide different values even for apparently similar indicators. One of the main drawbacks of the Emergy Method Assessment is that, as with all energy methods, it does not properly treat heat fluxes and in general flows of energy with different exergy factors (ratio of exergy to energy).

Therefore, for engineering system and process analyses, Exergy Analysis is a more useful tool because it is not affected by the limitations of an energy method. The "cumulative exergy cost" is the amount of primary exergy that goes into a product, and provides an effective measure of the real consumption of resources per unit of product (*ibid*).

Summarizing, emergy seems easier to compute, provided that the ecological network is known, while exergy seems to have a better theoretical basis.

2.3 Previous LCA Studies of Transportation Systems

Chester and Eisenstein (2012) conducted a life-cycle assessment study for the Metropolitan Area of Los Angeles considering environmental impacts of the vehicle, infrastructure and energy production. This study intended to capture a more comprehensive footprint for each of the modes, and to identify ancillary and supply chain processes often ignored. Chester and Eisenstein analyzed the energy consumption and air emission effects of Los Angeles Metro's Orange Bus Rapid Transit (BRT) Line and the Gold Light Rail Transit Line. Although life cycle inventories were developed for the Orange Line, Gold Line and a competing automobile trip, the complete life cycle assessment was not done for the automobiles, as the net energy and environmental impacts were only evaluated for the Orange and Gold Lines. Furthermore, the energetic analysis was performed exclusively as a result of an energy balance, without any suggestion of an Exergetic Life-Cycle Assessment (ExLCA).

Other LCA studies of transportation systems have typically analyzed a single mode of transportation with different fuel alternatives. The Madrid BRT transportation system has been analyzed within an LCA framework for the energy consumption and greenhouse gases (GHG) emissions of natural gas, biodiesel and diesel buses (García-Sánchez, López-Martínez, 2012). Alternatively, a study in the city of Kaunas, Lithuania, analyzed the life cycle assessment of five alternative "fuel chains", i.e., alternative fuel options, for two public transport alternatives: the midi urban bus and a similar type of trolleybus. This study compared the weighted damage originating from the compressed biogas fuel; the electricity generation for trolleybuses using natural gas; the electricity generation for trolleybuses using heavy fuel oil; the diesel option for the urban bus; and the compressed natural gas for the urban bus (Kliucininkas, L., 2012). This comparative life cycle assessment suggested that the biogas-powered buses and electric trolleybuses could be considered as the best alternatives to use to modernize the public transport fleet in Kaunas. While this particular study considered two transportation modes, it is relevant that its emphasis lied more in comparing five different alternative fuel chains than in two different transportation modes. Furthermore, as with previous studies, there was no suggestion of an Exergetic Life-Cycle Assessment in this paper.

As of this writing and after review of the available research databases, there has been only one LCA study which includes exergy; no studies which compare the 3 modes of BRT, subway, and automobiles; and no study performed in any transportation mode in Mexico City, individually nor as a comparison between them. The above information is summarized in Table 2-1.

Table 2-1. LCA Studies of Transportation Systems.

Study Attributes	**Los Angeles**	**Madrid**	**Kaunas, Lithuania**	**Mexico City**
Full LCA study in Transportation Sector	✓	✓	✓	N/A
Comparison of Transportation Modes	✓	×	×	N/A
Comparison of fuel alternatives	×	✓	✓	N/A

2.4 Life Cycle Inventory and Impact Assessment Models for Transportation

Models that have been recently developed to assess energy, emissions and other environmental impacts, from a perspective that is closer to a full Life-Cycle Assessment, include the following.

2.4.1 The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)

The Argonne National Laboratory’s Systems Assessment Group first developed, in 1996, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET). Sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), GREET allows a full Life-Cycle Assessment platform for the analysis of various combinations of vehicle and fuel technologies. It must be pointed out that GREET does not include the life cycle of the infrastructure nor the manufacturing of the vehicle itself, but only the life cycle stages of the fuel.

The most recent versions are the GREET1 2017 version for fuel-cycle analysis and the GREET2 2017 version for vehicle-cycle analysis. Both are available at https://greet.es.anl.gov/

GREET evaluates the fuel cycle from wells to wheels (also known as the Well-To-Wheel analysis) and the vehicle cycle all the way to material recovery and vehicle disposal.

Vehicle technologies included in GREET are: conventional internal combustion engines, hybrid electric systems, battery electric vehicles, and fuel cell electric vehicles. Fuel/energy options include petroleum fuels, natural gas-based fuels, biofuels, hydrogen, and electricity.

LCA results include energy use (by different energy sources), emissions of greenhouse gases (in terms of CO_2 equivalent; primarily carbon dioxide CO_2, methane CH_4, and nitrous oxide N_2O) and emissions of seven criteria air pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 micron (PM10), particulate matter with size smaller than 2.5 micron (PM2.5), black carbon (BC), and sulfur oxides (SOx). GREET is thus an inventory model, and does not evaluate impacts.

GREET was developed as a multidimensional spreadsheet model in Microsoft Excel. This public domain model is available free of charge for anyone to use.

GREET simulates three vehicle classes: a) passenger cars b) light duty truck 1 (gross weight < 6000 lbs) and c) light duty truck 2 (gross weight < 8500 lbs). Since GREET does not simulate passenger buses, nor subway systems, it has no capacity to compare between modes. As mentioned earlier, this is one of the expected contributions of this work.

2.4.2 Simapro

Considered to be the premier Life-Cycle Assessment software available at this time, Pré Sustainability's Simapro greatest strength lies in the many tools and databases it carries, along with its multiple impact assessment methods and its ability to run Monte Carlo analyses, both in the data and among products, among other features.

For the purposes of this dissertation, however, its greatest drawback is that it is not specifically geared for transportation. Although Simapro was used to solve the case study of Mexico City's three transportation modes, the development of a customized LCA-based tool to compare transportation modes surpasses Simapro's usage.

2.4.3 Mobitool

Mobitool is the Swiss platform for mobility management tools, and processed environmental data. It incorporates factors for the environmental and energy balance as well as three tools: Mobicheck, Comparison Computer and Mobiplan. It has been developed with the intention to aid in the mobility management process, i.e. transportation management. In Switzerland, the Mobitool factors are considered the de facto standard for the life cycle assessment of mobility (transportation).

Mobitool was developed through a joint commitment of the SBB, Swisscom, Swiss Energy, the Federal Office for the Environment (FOEN), and Öbu. It is available at www.mobitool.ch and at https://www.mobitool.ch/de/tools/vergleichsrechner-15.html

The Mobitool factors are summarized in an Excel file that contains the emission and environmental values of more than 150 transport options. The transportation modes included in Mobitool are air transportation, buses (freight), public transportation (streetcar, passenger buses and trolleybus), helicopters and cable cars. Additionally, it models passenger cars, but does not include subway in its available modes. While Mobitool allows the user to compare between two different transportation modes, since it includes no information on the life cycle of the infrastructure, the user cannot input the number of stations, or in fact, any information related to the infrastructure.

The Mobitool factors were recently evaluated (2016), updated and expanded, by a private corporation (Treeze Ltd.). Mobitool covers the operation, energy supply, vehicle production and maintenance as well as infrastructure for every transportation option.

Results from Mobitool display the following indicators:

- Primary energy / primary energy non-renewable
- Greenhouse gas potential (CO_2 eq.)
- Particles (PM10 and PM2.5)
- Nitric Oxides (NOx)
- Non-methane hydrocarbons (NMVOC)
- Resource load (ReCiPe, new feature)
- Environmental impact points 13 (UBP'13, new feature)

Mobitool has three important disadvantages. First, it has been developed with a Swiss focus that is not equivalent to nor includes world data, and occasionally does not even contain data for the rest of the European Union. Second, it does not support the latest versions of the Ecoinvent database (versions 2.2 and higher) since its developers decided not to support later Ecoinvent versions in order to maintain homogeneity with the previous Mobitool v. 1.0. Third, it does not aggregate inventory emissions into health impacts.

2.4.4 Fuel and Emissions Calculator

The Fuel and Emissions Calculator (FEC), developed at the School of Civil and Environmental Engineering of Georgia Tech, had the original intention of providing public transit agencies with a tool to assist them to choose between different vehicles, but mostly then-existing and anticipated electric options. This calculator makes it possible to compare the performance of various vehicle technologies, particularly relative to their purchasing costs, operating and maintenance costs, including energy/fuel efficiency, and their ability to reduce GHG emissions. For fleets, the estimation of criteria air pollutants is also included. The FEC calculator, also a spreadsheet-based calculator, is available at http://fec.ce.gatech.edu/ free of charge to public agencies worldwide, through the Federal Transit Administration (FTA).

Current vehicle and propulsion systems in FEC include:

- Cars, buses and Vans: Conventional Internal Combustion Engine (ICE), CNG/LNG, All-electric, Hybrid-electric, Plug-in hybrids and Fuel-cell electric vehicles
- Rails: All-electric rail and diesel-electric rail

There is also a web-based version of FEC, and other vehicle types, such as heavy-duty truck or passenger cars, are under development. There is also a cost-effectiveness module to be added to FEC in the future.

The greatest disadvantage of the FEC calculator is that it does not take a full Life-Cycle approach, but rather only calculates emissions and energy consumption during the vehicle operation stage.

2.4.5 The Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE)

The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a spreadsheet-based LCA and Life-Cycle Cost Analysis (LCCA) program designed by the Consortium on Green Design and Manufacturing from the University of California-Berkeley, and is available free of charge at https://rmrc.wisc.edu/palate/

PaLATE was designed to serve as a tool in the assessment of the environmental and economic effects of pavement and road construction. User inputs include the initial designs and initial construction material, along with maintenance material and processes, equipment, and cost for a project. PaLATE's outputs include:

- Energy consumption (MJ)
- Water consumption (kg)
- Carbon dioxide emissions (Mg)
- NO_x emissions (kg)
- Particulate matter (PM10) emissions (kg)
- Sulfur dioxide emissions (kg)
- Carbon monoxide emission (kg)
- Leachate information (including mercury, lead, RCRA hazardous waste generated, and both cancerous and non-cancerous human toxicity potential)

While PaLATE is a full Life-Cycle Assessment-based spreadsheet model, its greatest shortcoming is that it only evaluates road and pavement construction, not including the LCA of any transportation mode at all, nor any possible comparison among them.

2.4.6 Pavement LCA

Formerly known as the Athena Sustainable Materials Institute's Impact Estimator for Highways, Pavement LCA's latest 2.3.0101 version was released in January 2018 and is available, prior login registration, at https://calculatelca.com/software/pavement-lca/get-the-software/#new_tab

The Pavement LCA tool has both a desktop and a web-based version –which includes only a Life-Cycle Cost Analysis capability- and only the web version will be developed from this point forward. Pavement LCA applies a full LCA-based analysis for Canadian and select US regional materials manufacturing, roadway construction and maintenance life cycle stages. The desktop application contains a library of over 150 roadway designs, while the web app's library includes over 48 existing Canadian roadway designs. The user has the flexibility to specify unique pavement systems, and can also input use-phase operating energy and apply built-in pavement vehicle interaction algorithms, if desired, to be included in the final LCA results.

Pavement LCA allows for the comparison of multiple roadway design options over several expected lifespans. Pavement LCA was made possible by support from the Cement Association of Canada and Athena Institute members.

Pavement LCA was built using the same methodology as the Impact Estimator for Buildings. It provides a life cycle inventory profile for a given three-dimensional roadway design. The inventory results comprise the flows from and to nature: energy and raw material flows, plus emissions to air, water and land. The software reports life cycle impact assessment results by activity stage and enables easy comparison of different design options.

Pavement LCA inputs are roadway construction and rehabilitation parameters. The materials, energy, equipment and transportation databases for this tool include those sourced from the Athena Institute, the US LCI Database, and others.

Consistent with the US EPA's TRACI methodology, Pavement LCA results cover the following environmental impact categories: global warming potential, acidification potential, human health respiratory effects potential, ozone depletion potential, smog potential and eutrophication potential.

The software calculates the environmental impacts of the following life cycle stages: material manufacturing, including resource extraction and recycled content; on-site construction; use phase and maintenance and replacement effects. It is noteworthy that demolition and disposal phases are excluded, since highways have long service lives.

Pavement LCA is another full LCA-based tool, in spite of the final life cycles stages being excluded, but its main drawback is that is only calculates roadway construction and use, and does not consider any transportation mode's LCA environmental effects, nor has the ability to compare between them.

2.5 Advantages of TransportLifeCAMM over Similar Models

Major contributions of TransportLifeCAMM over similar LCA-based models is:

1) It includes the full life cycle of the infrastructure surrounding each transportation mode, as well as the vehicle and fuel. Other models address vehicles/fuel or infrastructure, not both.
2) It goes beyond the inventory level to evaluate impacts, as specified by ISO 14040.
3) It includes multiple transportation modes (cars, buses, and subways).

4) In the description of the infrastructure subsystem, other models and studies have not included any calculations regarding the stations and depots supporting the transportation mode, or at least not in the level of granularity that TransportLifeCAMM does.
5) Furthermore, TransportLifeCAMM gives an overview of the exergetic life cycle balance for each transportation mode, a metric that has hitherto not been included into any of the above-mentioned LCA-based transportation models.

Hence, a more accurate representation of the true environmental impacts associated with choosing a transportation alternative over another is provided by TransportLifeCAMM.

2.6 Air Quality and Transportation in Mexico City

Air pollution is an almost universal problem in most large cities and metropolitan areas around the world, but in the case of Mexico City, its unique geography and meteorology, along with its population density, its chaotic growth during the second part of the twentieth century, as well as the absence of adequately planned transportation infrastructure and services during that growth period, have resulted in a distinctive challenge in terms of air quality control. Geographically, Mexico City is a closed basin surrounded by mountainous ranges mostly to the west, south and the southeast, which hinders significantly the dispersion of pollutants. Furthermore, its mean altitude of 2,200 m (1.367 miles) means that even physical factors such as the vapor pressure of fuels have to be readjusted and recalculated to accurately reflect the reality of exhaust emissions on the ground (Gamas, 1999).

Mexico City's average annual temperature was 17 ˚C (62.6˚F) during 2010, with a maximum temperature of 34˚C (93.2˚F) during the month of May 2010, and a minimum temperature of -5˚C (23˚F) in November 2010 (Mexico City's Ministry of the Environment, 2010). Accumulated annual precipitation in 2010 was 700 mm (27.55 in), of which 556 mm (21.88 in) were recorded during the months of the rainy season (April-October). UV solar radiation is typically the highest from March to August, with

“High” and “Extremely High” values in the UV Solar Radiation Index (*ibid*). The highest ozone concentrations were recorded during the dry, hot season (March-May, 2010, as occurs typically in all years), while the highest concentrations for the remaining criteria pollutants (SO_2, NO_x, CO, Particulate Matter (PM) and Pb) were recorded during the dry, cold season (November to February). During the months of June-October, rainfall typically decreases the concentration of all pollutants across the board (*ibid*). Considering that the highest population densities are found to the north of Mexico City and the south of the neighboring State of Mexico, (i.e., the north of the Mexico City’s Metropolitan Area (MCMA), and that most of the industrial and manufacturing facilities are similarly found to the north of the MCMA, the maximum concentrations for PM-10, NOx, CO and SO_2 were recorded to the north of the MCMA during 2010, as expected, and the maximum values for secondary pollutants such as ozone were recorded to the south of the MCMA, equally as expected, since local winds blow predominantly in a north to south direction in the MCMA, and the mountainous ranges to the south of Mexico City prevent the further dispersion and deposition of ozone, resulting in higher concentrations being recorded there.

Mexico City has thus been the focus of numerous scientific studies (Díaz, 2001; Múgica, 2003; Mendoza-Dominguez, 2010) and has also been the recipient of significant efforts, both from the public and private sectors, in ameliorating its air quality for the last two decades. Receiving substantial input from both the international and national scientific community, an air quality management strategy has been put in place and fine-tuned over the years, with the end result of a decreasing historical trend for the concentrations of all criteria pollutants. Taking 1989 as the base year, SO_2 and Pb concentrations have been reduced by 88% and 98%, respectively, while ozone and PM-10 concentrations have decreased 39% and 68%, respectively (*ibid*). Ozone is currently the most persistent problem in the MCMA, as the number of days in which the hourly standard was exceeded is still significant (154 days in 2011, which represents 42% of the year; according to the Federal Ministry of the Environment). Nevertheless, this number is substantially lower than the number of exceedances recorded at the beginning of the last decade, i.e., 323 days in the year 2000 (*ibid*). During 2016, there were only 10 days on which the exceedance of the ozone hourly standard made it necessary for preliminary non-attainment limitations to traffic (i.e., “Non-attainment Phase 1”) to be enacted.

The updated count of “clean days” -those with readings of up to 100 IMECAS in Mexico City and its Metropolitan Area can be accessed through Mexico City’s Ministry of the Environment’s website: http://www.aire.df.gob.mx/default.php?opc=%27aqBhnmOkYg==%27.

The exorbitant, unplanned and frequently illegal growth of Mexico City and the MCMA during the second half of the twentieth century resulted in an insufficient transportation infrastructure, unable to meet the demand, which in turn led to the explosive growth both in private automobiles and bus rapid transit buses. The subway system (Metro), built mainly during the last years of the sixties and throughout the seventies, provided much needed relief initially, but gradually became insufficient also. Consequently, public demand for satisfactory and environmentally sustainable transportation modes is relevant in the MCMA.

The increase of motorization in Mexico is due to the following factors: the increase in per capita income, the availability of inexpensive vehicles (both old and new), and the relatively low cost of transport fuels, mainly gasoline and diesel. Other factors that have contributed to the increase in energy use and greenhouse gas emissions from the transport sector include the inadequate enforcement of vehicle emission standards, the neglect and frequent omission altogether of transportation needs in urban development plans, and insufficient public transportation. Additionally, fuel pricing in Mexico has remained stable over the last decades, and fuel prices are among the lowest for countries within the Organization for Economic Co-operation and Development (*Low Carbon Development for Mexico,* Chapter 5).

Following historical trends and the pattern of motorization growth worldwide, projections estimate that the national fleet will increase from 24 million vehicles in 2008 to around 70 million vehicles in 2030. Thus, it is expected that greenhouse gas emissions will increase from 167 Mt CO_2e in 2008 to 347 Mt CO_2e in 2030, with 72 percent of the emissions and energy consumption generated by private vehicles. Total emissions are expected to increase from 659 $MtCO_2e$ in 2008 to 1,137 Mt CO_2e in 2030, with the percentage from transport rising from 25 percent to 31 percent (*ibid*).

In order to reduce these emissions and energy use, encouraging modal shifts –from private vehicles to public transportation alternatives—and a more effective approach to urban land-use, along with better fuels and technology, have been suggested as the primary public policies to adopt.

Johnson, Alatorre *et al* have suggested that by introducing Bus rapid transit (BRT) systems in Mexican cities with more than 750,00 inhabitants and having a target of 1.5 kilometers per 100,000 inhabitant of BRT lanes by 2030, equivalent to 122 lines of BRT systems, for a total of 1,830 kilometers nationwide, significant positive impacts could be achieved. Specifically, they have calculated that the introduction of BRT would result in a maximum annual emissions reduction of 4.2 Mt CO_2e per year and a net benefit of mitigation of 50.5 $/t CO_2e (*ibid*).

From the total 659 Mt of CO_2e/year that were generated in 2008, 167 Mt proceeded from the transport sector, and were distributed as follows: 93.3% for motor transportation; 3.7% for air transportation; 1.7% for railroad transportation and 1.3% for maritime transportation. (PNCC 2009-2012). Additionally, motorization has continued to increase over the last decades. In 2010 there were slightly over 22,000 registered vehicles in the country, compared against 6,900 vehicles registered in 1990; additionally, it is estimated that there were between 2.5 million and 5 million illegal vehicles (introduced illegally into Mexico from the United States). The motorization index increased from 85 vehicles per 1000 inhabitants in 1990 to 197 in 2010, which is actually 236 if illegal vehicles are included. It is forecast that since the increase in vehicular motorization will be sustained, by 2030 Mexico will have 491 vehicles/inhabitant, with an annual growth rate of 4 percent. There will be 65.5 million vehicles in circulation for the 134 million inhabitants of Mexico in 2030, in a suburban and not very densely-populated environment, if the current patterns of urbanization hold, in which vehicles will have to cover great distances.

The future scenarios that these figures portray are not very encouraging. According to the MEDEC study, from the 167 Mt of CO_2e/year emitted in 2008, if nothing is done, emissions from transportation could increase to 347 Mt CO_2e/year in 2030, while the total emissions from all sectors would rise from 659 Mt to 1,137 Mt, which also means that transportation's weight in the total GHG emissions could rise from 25% to 31%. On contrast, scenarios proposed in the study "Low carbon growth, a potential for Mexico," the scenario for the year 2030 for the transport sector is only 225 Mt CO_2e/year.

According to the Mexican federal government's strategy, contained in the Special Climate Change Program (PECC in Spanish, published in August 2009), the objective is to reduce GHG emissions by 50%, relative to those emitted on the year 2000. Moreover, there is an additional goal to emit 339.4 Mt CO_2e/year in the year 2050, from which 121.7 Mt CO_2e/year would correspond to transport. This imposes intermediate goals for transport emissions: 168.2 Mt for 2020 and 185.0 Mt for 2030. Given that the tendency is for a figure of 347 Mt CO_2e/year, and the goal is 185 Mt CO_2e/year, this can be interpreted as an expected reduction of 162 Mt CO_2e/year.

To reduce the above-mentioned 162 Mt CO_2e/year, a special analytical effort to identify the areas of potential reduction had to be undertaken. Two studies were commissioned, one by McKinsey & Co and the Mario Molina Center, and another one by the World Bank (Study on the Decrease of Carbon Emissions, "Estudio sobre la Disminución de Emisiones de Carbono", MEDEC). The first study proposes the reduction of 80.1 Mt CO_2e/year and the second one of 130.7 Mt CO_2e/year. The following table, Table 2-2, summarizes the proposed potential reductions in both studies.

Table 2-2. Areas of opportunity for emission reduction identified in the MEDEC and McKinsey studies.

Potential Reduction by 2030	MEDEC	McKinsey
A. Modal Changes and Urban Development	**55.8**	**23.1**
Route Optimization for Public Transport 96.6 (benefit)	31.5	--
Urban Densification 66.4 (benefit)	14.3	--
BRT-type transportation systems 50.5 (benefit)	4.2	13.7
Non-motorized transportation 50.2 (benefit)	5.8	--
Subway (Metro)	--	9.4
B. Technologies and demand management	**41.9**	**57**
Vehicle Inspections at the Border 69.0 (benefit)	11.2	--
Vehicle Inspection in 21 large cities 14.5 (benefit)	10.6	--
Vehicle regulations 12.3 (benefit)	20.1	42
Biofuels	--	15
C. Freight	**33**	**--**
Freight logistics on highways 46.3 (benefit)	13.8	--
Freight through railroad 88.7 (benefit)	19.2	--
TOTAL	**130.7**	**80.1**

The costs associated with implementing the above are negative if the benefits in time, health, accidents and investment are considered. As a result, the net investment in the transportation sector is negative, that is, without considering the benefits in the reduction of GHG, which suggests that implement these actions will be advantageous.

According to the Global Environmental Fund (GEF), the following are the emissions in gram per kilometer, the average occupancy (number of passengers), and the resulting emissions in gr-passenger/km for different modes of transportation, as shown in Table 2-3:

Table 2-3. Emissions in Gr-passenger/km for Different Modes of Transportation (Global Environmental Fund).

Mode	Emissions (gr/km)	Passengers	gr-passenger/km
Taxis	300	0.5	600
Cars	403	1.2	336
Motorcycles	220	1	220
Minibuses	1097	15	73
Buses	1097	65	17
Articulated Buses	1000	130	80
Bicycles	0	1	0

Source: Global Environmental Fund

Using the criteria established in the MEDEC study, of 1.5 km of major avenues for BRT service for each 100,000 inhabitants in cities over 750,000 inhabitants by the year 2030, 1,059 km would be needed for 31 cities. In 2030, almost 58% of Mexicans will live in these 31 cities.

The subway system, or "Metro," long considered the best transportation alternative in Mexico City, currently has 12 lines (routes), covering a total of 201.38 kilometers (122 miles). It has an estimated transportation capacity of 5,170, 890 seats per day, in a single-direction basis, and its recorded maximum of passengers transported occurred on November 12, 2010, with 4,847,089 persons (STC, 2011), with a daily ridership of 4,616,264 (as of 2013), and an annual ridership, measured for the year 2015, of almost 1.624 billion (1,623 828, 000 642 passengers) (STC, Operating Figures). The Metro is commonly referred to as the "zero emissions" transportation alternative in Mexico City. However, this does not account for the fact that, although emissions are not visible on-site, the electrical energy required to run the subway trains and all their auxiliary and support equipment (fans, escalators, elevators, lighting within the stations, turnstiles, etc.) is provided by the Federal Commission of Electricity (CFE), mainly from the “Acolman” power plant (which burns natural gas) and the “Tula” power plant (which burns fuel oil). A noteworthy amount of SO_2, NO_x and PM emissions are directly attributable to both of these facilities. Therefore, an accurate mass, energy and exergy balance must be performed to precisely account for the emissions that are generated throughout the life-cycle of the Metro.

The most recent bus rapid transit (BRT) system in Mexico City, the Metrobus, currently has seven lines. Line 1, the subject of this study, started operations on June 19, 2005, along the distance that is roughly parallel to the Metro’s Line 3, and was further enlarged to the south on March 13, 2008. The Metrobus buses run on ultra-low sulfur diesel (ULSD) with a concentration of 350 ppm S or less as their fuel.

The third transportation mode analyzed in this dissertation was a private automobile, with the average characteristics of age, make, fuel (gasoline, premium or regular, or alternatively, diesel), as well as the average speed in Mexico City, which have been studied and are well known (Mendoza-Dominguez, 2010).

2.7 Contribution of TransportLifeCAMM to Air Quality and Transportation in Mexico City

By offering an impartial, unbiased and equitable framework for comparison, based on the same methodology of environmental impact assessment, and on the same functional unit (g of impact/pollutant per passenger*km), it is expected that TransportLifeCAMM will guide stakeholders, interested citizens and decision makers towards more sustainable decisions. While it is acknowledged that public officials and policy makers usually must consider a variety of factors when deciding among transportation modes to solve a particular transportation challenge, it is hoped that the results of TransportLifeCAMM will provide them with a better long-term perspective, thus informing their decisions.

Chapter 3

METHODOLOGY

3.1 Methodology for Research Objective 1 (Development of TransportLifeCAMM)

In the process of creating the Urban Passenger Transportation Life-Cycle Inventory for Comparison Across Modes Model (hereafter referred to as TransportLifeCAMM), great attention was given to the development of a methodology that was not only internally consistent but also functionally equivalent across all modes under study. This was done with the intention of providing fairness as the starting point for comparisons to all modes, as well as scientific objectivity and reproducibility. Moreover, by adopting a common methodological framework, it is expected that future studies can more easily build upon the findings of this research.

Following after Chester and Horvath (2008, 2009) and Schmied & Mottschall (2010), it was decided that not only the vehicle operation, or in fact, the vehicle's life cycle, but also the contributions of its surrounding infrastructure would be accounted for in order to properly gauge the environmental effects of each transportation mode. Further, it was decided that the results of the life cycle inventory, and in TransportLifeCAMM, would be expressed in grams of impact (or pollutant) per passenger-kilometer.

It is understood that life-cycle assessments for passenger transportation often compare travel by using vehicle-kilometers traveled (VKT) or passenger-kilometers (PKT) as a functional unit (Chester & Horvath, 2010). For instance, it is fairly common to express the greenhouse gas impacts of transportation as CO_2/PKT_1, i.e., the carbon dioxide emissions resulting from a passenger traveling one kilometer. This functional unit has the advantage of being intuitive for comparing the impacts of different transportation technologies. As pointed out in previous studies similarly analyzing different transportation modes over metropolitan areas (Chester and Eisenstein, 2012, p. 28), a primary goal of passenger transportation modes is to provide mobility for people, and in this sense, the per PKT functional unit is the most appropriate functional unit for such evaluation. It is noted that when public transit life cycle inventories are normalized per VKT, results often show an order-of-magnitude larger than automobiles (*ibid*). Further, the per VKT functional unit is useful for evaluating corridor or regional emission profiles but does not provide a ground for comparing the energy and environmental effectiveness of moving individual passengers (*op. cit*., p. 29).

There are several limitations to the use of CO_2/PKT as a unit of analysis. One of these disadvantages is that transportation modes differ drastically in terms of the value and quality of service for equivalent distances traveled. Moreover, the subway and BRT modes offer benefits that cannot be measured in terms of PKT, such as greater productivity during travel and ease of use for disabled or elderly passengers. Addressing these issues, however, is beyond the scope of this study. Given that the goal and scope of this study is primarily geared towards assessing the aggregate emissions impacts resulting from a given transportation mode, and not an exhaustive analysis of the many possible costs or benefits of investment in that transportation alternative, the functional unit of PKT is considered adequate for our purposes.

It is acknowledged that the use of PKT as a functional unit does not completely account for the fact that the three transportation modes operate under inconsistent temporal resolutions. Thus, it becomes especially important to calculate the life cycle subsystem of energy consumption and emissions, which will therefore first be evaluated within their respective temporal resolution: a vehicle lifetime of 12 years for BRT buses; an average sedan lifetime of 15 years in Mexico City to normalize; and the electricity consumption determined for 2012 for the subway system, since this is the most recent year for which the official data and emission factors, specifically for the Mexican electricity mix, are available within Simapro. The average lifetime of subway trains will be considered to be 35 years. Furthermore, fuel consumption for 2012 will be used also for cars and buses.

As a result, all life cycle subsystems are first normalized to a per VKT common functional unit for aggregation, and ultimately normalized to a per PKT functional unit to provide a fundamental comparative unit for ease of comprehension. This methodology is similar to the one proposed in Chester & Eisenstein (2012).

3.1.1 General Methodological Procedure

The general methodological procedure for the development of TransportLifeCAMM is illustrated in Figure 3-1. Once the conceptual framework for the solution of the three transportation modes is set, both traditional and exergetic Life-Cycle Assessments are carried out, under the hypothesis that the subway (metro) is the transportation mode with the least environmental burdens and the lowest emissions in a g/passenger*km basis. The null hypothesis is then that there is no difference among the three transportation modes.

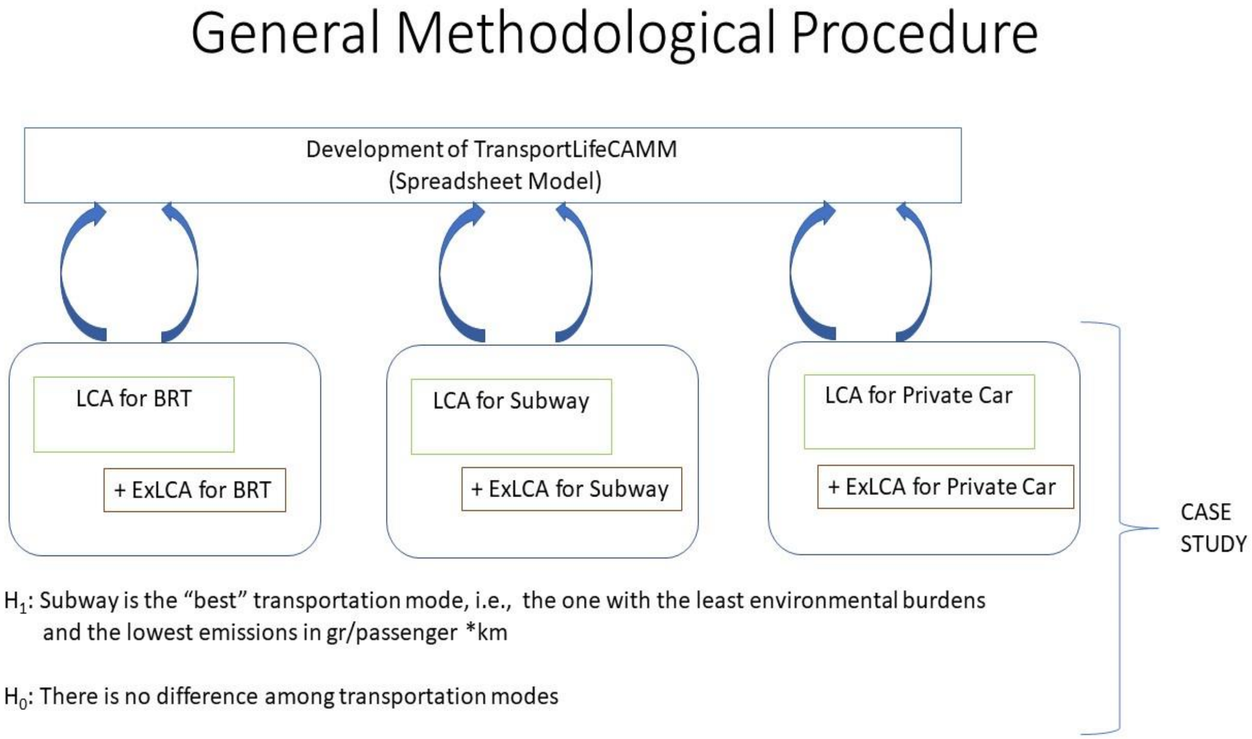

Figure 3-1. General Methodological Procedure for the Development of TransportLifeCAMM.

Each transportation mode was initially considered as a "system" with three "subsystems": the vehicle subsystem, the infrastructure subsystem, and the energy subsystem. While conceptually this aided in the definition of the system boundaries for each mode, in practice, that is in the simulation of these subsystems within the Life-Cycle Assessment Simapro© software, the energy subsystem was embedded within the vehicle subsystem.

The system boundaries for each mode will be detailed in subsequent sections. In principle, however, the estimation of the environmental impacts for all modes was carried out using a material flow analysis and the chain-block analysis characteristic of a process-based LCA.

Further analysis of the characteristics of each subsystem led to the creation of "modules" for each subsystem. These modules are the closest representation of a distinct unit process within Simapro. Moreover, the motivation behind these "modules" was to provide the future users of

TransportLifeCAMM with the ability to scale down or up, or in other words, to “customize” their own “system” or transportation mode, by easily adjusting the number of these modules.

These modules were of particular relevance in the infrastructure subsystem, and more specifically, in the subway (Metro) and BRT (Metrobus) modes. In each of these cases, the infrastructure subsystem was further divided into the Station, Depot and Road/Railway modules.

Regarding the hierarchy of the subsystems relative to each other, it was decided that for all modes of transportation, the vehicle subsystem, with its corresponding lifetime, should be the first in hierarchy within the whole system, i.e., the contributions of all other subsystems are measured relative to the vehicle subsystem. This is because the vehicle, along with its embedded energy or fuel subsystem, is the most significant subsystem, since the operation of the vehicle generally accounts for over 80% of the emissions and the largest share of the overall environmental impact.

Given the substantial diversity of lifespans, technologies, construction methods and other variables for the three modes, the general methodology to assess the environmental impacts of the infrastructure relative to the vehicle subsystem can be described as follows.

Step 1. Calculate the “total materials inventory,” or more precisely, the “total materials flow,” for each of the smallest elements within each subsystem. This is the calculation of all the inputs and outputs that went into the construction, or manufacturing, respectively, for each of the modules: station, depot, and unit kilometer of road for the BRT; unit kilometer of road for the car; and unit kilometer of railway for the subway, along with station and depot module for the subway as well. Although no multiplication by emission factors has yet taken place, units at this point would be grams of impact (pollutant, etc.) per grams (mass) of each the elements, or reference flows, that comprise each module. To recall, an “elementary flow,” is the name given in an LCA context to emissions and extractions to and from the environment. The grams of impact (pollutant) will appear once the multiplication by emission factors takes place. At this point, units are still grams (mass) of reference flow.

Step 2. Given the different lifespans for all elements within any single module, and more importantly, the different lifespan between the modules and the vehicle itself, calculate a ratio of lifetimes of the vehicle's expected (or assumed) lifetime relative to the years of expected lifetime for each module. Multiply the above material flow by this lifetime ratio. For instance, if the lifetime of a car is 15 years, and the lifetime of a station is 30 years, the lifetime ratio is declared in such a way as to ensure that the material flow of the car is multiplied by two. Since this is a ratio (of years), the units of this step continue to be grams (mass) for each reference flow.

Step 3. Multiply the above result by the number of modules present in each subsystem, i.e., number of stations, depots, and distance, in kilometers of road or railway. Units continue to be grams (mass) of reference flow, but now they reflect the reality of an actual system under study, a specific line of BRT or subway, or a car and its attendant infrastructure, whether existing or proposed.

Step 4. In order to correctly allocate the impact (or "stress") of an infrastructure module relative to the "stress" or impact placed upon the network, divide the previous result by the vehicle-kilometers (alternatively called the "transport performance") of the network (road or railway). Thus, a measurement of the importance of each, now in units of grams per vehicle-kilometers is obtained.

Step 5. Use Ridership, the ratio between Vehicle-Kilometers-Travelled (VKT) and Passenger-Kilometers-Travelled (PKT), to convert results in g/VKT to g/PKT, as shown in Equation 3 - 1.

$$R = \frac{PKT}{VKT} \qquad \text{Equation 3 - 1.}$$

If the results from the previous step, reported in grams of mass per VKT are then divided by Ridership (sometimes called Occupancy), which has units of passengers, results are now expressed as the grams of mass per PKT. Now, if we multiply this result by the emission factors available within Simapro (in any of its databases), we obtain the grams of impact (pollutant) per PKT. It must be pointed out that it is standard procedure within LCA studies in transportation to divide the results obtained in g/VKT by the ridership, or occupancy, in order to obtain results in g/PKT.

In order to properly estimate the impacts associated with the construction of the infrastructure for the three modes, the first step was to calculate the production capacity of the most common earthmoving machinery and equipment, so as to replicate as closely as possible the work, and its corresponding environmental impacts, that occurred when the materials and resources for construction were originally hauled, moved, or otherwise transported. This process of machinery production computations was based mostly on Caterpillar's Manual (Caterpillar, 1999) and on the United States Army's FM 5-434 (US Army, 2000). Additionally, for each type of earthmoving equipment, such as bulldozers, graders, loaders, dump trucks, excavators, etc., three scenarios were established. In the first scenario, the production capacity of an average equipment was estimated. For the second scenario, the previous hours of operation for each machinery were doubled, making it twice as many hours of operation for the same average equipment in the same categories. The third scenario was the result of computing the hours of operation for the largest available equipment, in all categories. Since the production capacity of the largest equipment will be greater, this third scenario typically resulted in significantly less hours of operation than in the first scenario.

Since these were preliminary estimations necessary to compute the total materials flow in each case, the total hours of machinery operation are reported in this methodology chapter, in the corresponding sections for each transportation mode.

Regarding the algorithm for solution of the vehicle subsystem, a similar approach was taken. However, since the vehicle has the preeminent hierarchical position within the system, no adjustments regarding its lifespan (i.e., no lifetime ratio), nor allocation to the network's performance are necessary. Additionally, emission factors (for example, in the GREET model and in EPA's MOVES model) are given in g/VMT (alternatively, in g/VKT). Furthermore, for this dissertation, and as explained below, the USLCI database records for the onroad vehicles (bus and car), based on GREET and Moves, and already normalized to g pollutant/PKT, were used. These records computed the inventory and VKT values from MOVES, and normalized them by a specific ridership. As before, dividing the results in grams/VKT by ridership produces units of impact per PKT. Hence, the simplified steps for the vehicle subsystem are the following:

Step 1. Calculate the Vehicle-Kilometers-Travelled during the expected lifetime, and with fuel economy data, estimate the vehicle's energy consumption.

Step 2. Multiply the above by its corresponding emission factors, by type of fuel for the onroad vehicles and by electricity mix, for the subway train. Results are now in grams of impact (or pollutant) per vehicle-kilometer-travelled.

Step 3. Use the Ridership ratio to divide the above result and obtain the impact in units of grams of pollutant per passenger-kilometer-travelled.

As far as the energy subsystems for the onroad vehicles (BRT bus and Private Car) are concerned, and their being embedded within the vehicle subsystems, these were solved through the use of the corresponding records of the United States Life Cycle Inventory Database (USLCI, 2012). The information in these records was modified, scaled by the vehicles' weight, and otherwise supplemented by specific information on vehicle operation as available. The USLCI records were developed by the National Renewable Energy Laboratory (NREL) located at Golden, Colorado. Detailed spreadsheets for these records were obtained and modified to accurately reflect the system boundaries and assumptions, as well as the vehicles' characteristics, of the present study. These records have solved the "Well to Wheels" portion of the energy and vehicle subsystem analysis by using the Argonne's National Laboratory GREET model for the Well-to-Pump portion of the vehicle's life cycle -symbolized by yellow boxes in Figure 3-2—and the Environmental Protection Agency (EPA's) MOVES2010a model, for the fuel combustion portion (emissions and energy inventory) of the vehicle operation. These records had already been normalized to a passenger*km basis. Nevertheless, since the weight, vehicle performance (VKT) and occupancy ratios for each vehicle were different from those assumed in this study, the records were modified and recalculated accordingly as is detailed in the corresponding sections.

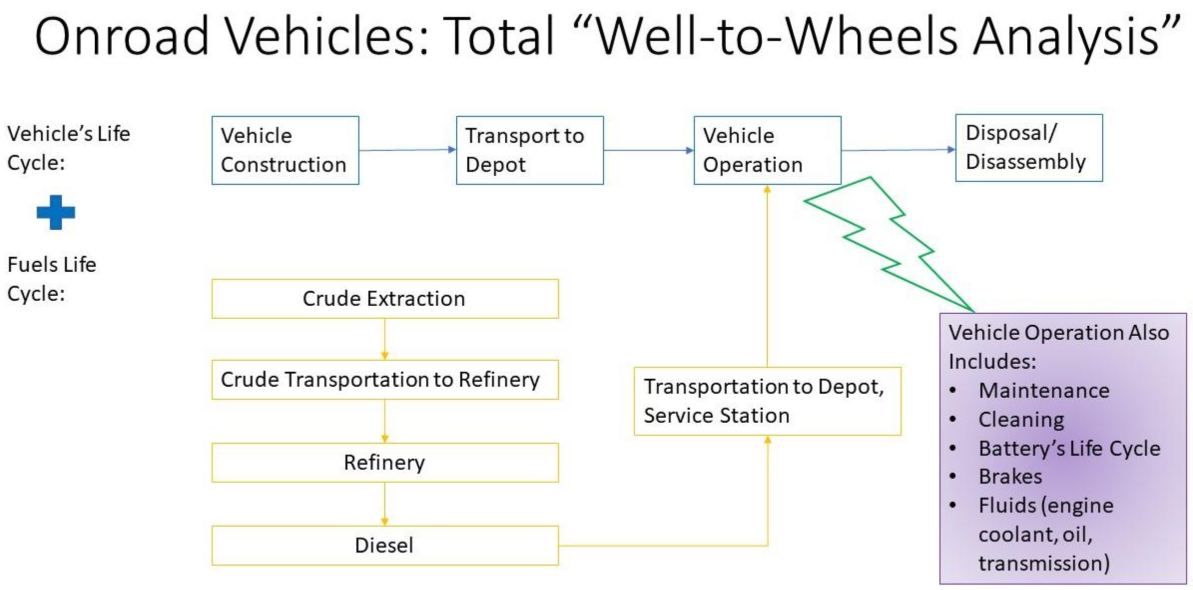

Figure 3-2. Well to Wheels Analysis for Onroad Vehicles

3.1.2 Attributional Life-Cycle Assessment for the Three Transportation Modes

Since the Life Cycle Inventory, and in fact, the full Life-Cycle Assessment for each of the three transportation modes under study was required for TransportLifeCAMM, these LCA studies were performed compliant to ISO 14040, which is detailed in Sections 3.2, 3,3 and 3.4. Since all LCAs were conducted in an attributional modeling mode, it is important to recall that this modeling is chosen when the environmental impact of a product and its sensitive points throughout its life cycle must be known. Additionally, attributional modeling is also chosen when comparing the impacts of two products with the same functional unit. Since all environmental inputs are outputs are summed from the cradle to the grave in attributional modeling, it is often referred to as an environmental footprinting.

3.1.2.1 Selection of Impact Assessment Methods

As a result of the data collection that occurred in the previous Inventory stage, a table called the Life Cycle Inventory (LCI) result is produced by the software This table can contain hundreds of “elementary flows,” which is the name given to emissions or extractions to and from the environment. In order to understand their meaning, ISO prescribes a step known as classification. The elementary flows from the inventory are assigned to the impact categories according to the substances’ ability to contribute to different environmental problems. Frequently, several emissions (or elementary flows) are assigned to the same impact category. The contribution of each elementary flow is determined using the IPCC equivalency factors, in the climate change impact category, or alternatively, by using other characterization factors that have been defined for the other impact categories. These characterization factors are determined by the impact assessment method utilized.

Therefore, the result of characterization is that each LCI result is multiplied by a characterization factor (CF), and then they are added to obtain an impact category indicator result.

The characterization phase presents several shortcomings:

- One emission (or elementary flow) can contribute to several impact categories. Although the ISO standard allows the possibility of splitting the elementary flow over two or more impact categories, this is generally not done. One substance can be the cause of different effects simultaneously.
- In many midpoint methods the units are defined as a reference to a substance. This results in relatively abstract units like CO_2 equivalents.
- Since the units of the results for each impact category are different, impact categories cannot be compared to each other, and the overall magnitude of impacts cannot be determined at this stage.

Due to the arbitrary units, the characterization results are not always easy to interpret.

ISO requires that characterization factors be based on well understood and documented science. It has prescribed that a scientific mechanism links the inventory result (an emission or elementary flow) to an “endpoint,” or area of protection.

Additionally, ISO suggests taking an indicator somewhere along the environmental mechanism and the LCI parameter that can represent the impact on the endpoint. Although it is not an ISO term, this has become known as the midpoint indicator. It is needed to calculate an endpoint indicator, but additional modeling steps are required.

This differentiation between endpoint and midpoint gives rise to the same distinction between impact assessment methods: depending at which level of the environmental mechanism these methods are located, they are called either midpoint impact assessment methods (if linked halfway along the scientific mechanism) or endpoint impact assessment methods (if at the end of the mechanism).

The ISO standard allows the use both of midpoint and endpoint impact category indicators. Generally, indicators that are chosen close to the inventory result have a lower uncertainty, while indicators near endpoint level can have significant uncertainties. However, indicators at endpoint level are much easier to understand and interpret by decision makers than indicators at midpoint. Mid-point level methods are sometimes called “a problem-oriented approach.”

From the available impact assessment methods contained in the software (Simapro, 2016), the following were selected for an initial screening:

- Cumulative Energy Demand (CED) method
- Cumulative Exergy Demand (CExD) method
- Impact 2002+ method
- TRACI method
- BEES method

Cumulative Energy Demand

The method to calculate Cumulative Energy Demand (CED) is based on the method published by Ecoinvent version 1.01 and was expanded by PRé for energy resources available in the Simapro database.

Characterization factors are given for the energy resources divided in 5 impact categories:

1. Non-renewable, fossil
2. Non-renewable, nuclear
3. Renewable, biomass
4. Renewable, wind, solar, geothermal
5. Renewable, water

Normalization is not a part of this method. In order to get a total (“cumulative”) energy demand, each impact category is given the weighting factor of 1.

Cumulative Exergy Demand

The Cumulative Exergy Demand (CExD) indicator is introduced to depict the total exergy removal from nature to provide a product, summing up the exergy of all resources required. In order to quantify the life cycle exergy demand of a product, the Cumulative Exergy Demand (CExD) indicator is defined as the sum of exergy of all resources required to provide a process or product.

Exergy is another way to express the quality of energy rather than the energy content. Both are expressed in MJ. Exergy is a measure for the useful "work" a certain energy carrier can offer. In this method exergy is used as a measure of the potential loss of "useful" energy resources.

Since this method was employed to achieve Objective 3 of this study, it is further described in Section 3.5.

TRACI 2.1

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a stand-alone computer program developed by the U.S. Environmental Protection Agency (EPA) specifically for the US, utilizes input parameters consistent with US locations. TRACI facilitates the characterization of environmental stressors with potential effects, including: ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health noncancer effects, fossil fuel depletion and land-use effects. For characterization, impact categories were characterized at the midpoint level. Research in the impact categories was conducted to construct methodologies for representing potential effects in the United States.

TRACI is a midpoint-oriented life cycle impact assessment methodology, one of its major disadvantages for this study, and the reason why it was ultimately discarded. Arguing that normalization and valuation are still under debate and because of possible misinterpretation and misuse, the authors of TRACI determined that the state of the art for the normalization and valuation processes did not yet support inclusion in TRACI and consequently, TRACI does not aggregate environmental impact categories.

Impact 2002+

This method uses elements of the CML 2000 and the Eco-indicator 99 method. Toxicity impact categories have been completely redeveloped, with more toxicity data included.

Among the methods initially considered but ultimately discarded, Impact 2002+ was eliminated because it is not fully adapted for inventory data from the Ecoinvent library and the USA Input Output Database 98, and therefore omits emissions that could have been included in the impact assessment. Since this study is geared mainly towards North America, and is particularly interested in emissions, the Impact 2002+ method was discarded as an option for the environmental impact assessment portion of this work.

BEES

BEES is the acronym for Building for Environmental and Economic Sustainability, a software tool developed by the National Institute of Standards and Technology (NIST). The BEES method uses the SETAC method of classification and characterization. The following six life cycle assessment impact categories are used by BEES:

1. global warming potential
2. acidification

3. eutrophication potential

4. natural resource depletion

5. solid waste

6. indoor air quality

Normalization is implemented as described in the report (Lippiatt, 2007) and weighting as described in Gloria et al. (2007).

In summary and after an initial screening whose results are listed in Section 4.1, in consideration principally of both the interest in orienting this research towards a North American perspective, using North American data as much as feasible, and the awareness that an endpoint method would best fit the objectives pursued in this study, BEES was chosen as the Impact Assessment method for this dissertation.

Weight Sets Available in the BEES+ Impact Assessment Method

Weighting, as the third step in the BEES+ method, following after the normalization phase and before the single score phase, is the way to move from the quantitative results of an LCA study to values-based, subjective choices. BEES+ offers the LCA practitioner a choice between three general weight sets, and a multi-stakeholder perspective. The difference between these two approaches is that the latter was developed through a panel of experts, which made this fourth weighting set a synthesis of the panelists’ perspectives on the relative importance of each environmental impact category in BEES+.

It must be noted that for all LCA runs and analyses in this dissertation, it was the USA’s per capita, for the year of 1997, EPA’s weighting set that was used. This was due to the fact that this weighting set was considered to best represent the relative importance of the infrastructure subsystem for all transportation modes.

For reference, Table 3-1 lists the four weight sets included in the BEES+ method, as well as the weights each set assigns to the environmental impact categories, respectively.

Table 3-1. Weight Sets Available in BEES+, with Weights for Each Impact Category

Weighting	USA per cap '97-EPA Weighting	USA per cap '97-Harvard Weighting	USA per cap '97-Eq Weighting	USA per cap '97-Stakeholder Weighting
Global warming	16	11	7.69	29.21
Acidification	5	9	7.69	2.99
HH cancer	5.5	3	7.69	7.58
HH noncancer	5.5	3	7.69	5.28
HH criteria air pollutants	6	10	7.69	8.87
Eutrophication	5	9	7.69	6.18
Ecotoxicity	11	6	7.69	7.48
Smog	6	9	7.69	3.49
Natural resource depletion	5	7	7.69	9.67
Indoor air quality	11	7	7.69	3.29
Habitat alteration	16	6	7.69	6.08
Water intake	3	9	7.69	7.78
Ozone depletion	5	11	7.69	2.09

3.1.2.2 Special features of the Simapro software and the Ecoinvent database

For the materials (fuels, construction/infrastructure materials, manufacturing materials, electricity, water, etc.) modelled for this dissertation within Simapro, the raw materials/extraction phase of the LCA, as well as the manufacturing and transportation phases, are included as considered by Simapro. Transportation of these materials, unless otherwise noted, is typically included by Simapro in the “Market” option within its databases. In the cases where the transportation of a material or product is explicitly included as a separate item, this is done in the understanding that this material’s transportation exceeds the distances normally assumed by Simapro, or the distance is precisely known.

Case in point, the transportation of the manufactured BRT 7300 Volvo bus, from the manufacturing plant in the Metropolitan Area of Mexico City, to the BRT's depot, is accurately known. Consequently, this distance is edited in the matching Simapro record, and modelled accordingly.

In addition to the differences between allocation and consequential modelling, and between unit processes and system processes, that originate the four different dataset versions implemented within Simapro, and that have been mentioned previously, Ecoinvent makes a further differentiation.

In Ecoinvent, there are two system models to carry out allocation. The first system model, "Allocation, cut-off by classification," also known as the cut-off system model, is based on the Recycled Content, or Cut-off approach. This was the only available system model in Ecoinvent versions 1 and 2. The Cut-off approach always allocates the primary (first) production of materials to the primary user of a material. Hence, if a material is recycled, no credit is given to the primary producer for supplying any recyclable materials. Consequently, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes.

Another characteristic of the Cut-off system model is that producers of wastes do not receive any credit for the recycling or re-use of products that result from any waste treatment.

The "Allocation, cut-off by classification" was named "Allocation, recycled content" and within Simapro it appears as "Alloc Rec." Since both unit processes and system processes are available for this system model, Simapro contains the "Alloc Rec, U" and the "Alloc Rec, S" datasets respectively.

In contrast, the model "Allocation at the point of substitution," also known as the APOS system model, follows the attributional approach in which burdens are attributed proportionally to specific processes. The APOS system model was previously called "Allocation, Ecoinvent default". The name was changed with the release of Ecoinvent version 3.2. Similarly, there are both unit processes and system processes for the APOS model; therefore, the “Alloc Def, U” and the “Alloc Def, S” datasets are available within Simapro.

A common usage in Ecoinvent to denote geographical regions for which a particular dataset is valid, and that has been replicated by other databases, is to use abbreviated country codes for these. Table 3-2 summarizes a few of the frequent country codes, expressly those relevant for this work.

Table 3-2. Common Abbreviated Country Codes in LCA databases.

Country or Regional Abbreviated Code, as it appears in the database	Country or Region Referenced
GLO	Global. Considered a valid average for all countries in the world.
RoW	Rest of the World. Since Ecoinvent v3.2 (2015), this code has replaced GLO, and has been adjusted for uncertainty.
RNA	North America
US	United States
MX	Mexico
RER	Europe. Average data for all member countries of the European Union
RLA	Latin America and the Caribbean

An advanced Simapro feature of which this work availed itself was the use of “parameters” or variables that can be defined within Simapro, and which allow user to model relationships within inventory data through mathematical expressions. These parameters were used for the sensitivity analysis portion of the LCAs, and to develop scenarios for analysis more expediently. Through the use of parameters, there was no longer a need to create multiple assemblies to model different “products” but rather, once the parameters had been defined, expressions based on those parameters were developed. Hence, the quantities of material and assembly inputs were then controlled by parameter expressions and different scenarios could be analyzed by adjusting parameters, instead of creating a new product assembly.

3.2 Methodology for Research Objective 2, Part 1 (Case Study for Mexico City’s BRT)

3.2.1 Goal and Scope Definition

The LCA for Mexico City’s Bus Rapid Transit (BRT) is an external study (i.e., conducted by someone not belonging to the Transit Authority in charge of the BRT), performed in an attributional mode of analysis. It has a third-order system boundary definition: all processes including capital goods (i.e., infrastructure) are considered within the system boundary. (Third-order studies include the infrastructure, or capital goods, while first-order studies only include the elementary flows). However, the capital goods are modeled in a first order model, i.e., only the production of the materials needed to produce the capital goods are included. For this specific LCA, capital goods are considered to be the roadway and the infrastructure (stations and depot) of the BRT system.

3.2.1.1 Goal

The general goal is to conduct a traditional LCA of Mexico City's BRT system, or to build the life cycle inventory and assess the environmental impacts of the infrastructure (roadway, stations and depot), and vehicle subsystems of the BRT system, throughout the life cycle. Ultimately, once the LCA of the BRT system has been concluded, its results will be compared against similarly-conducted LCAs for the subway system of Mexico City and for a private car. The results of these comparisons will provide the foundation upon which TransportLifeCAMM is built.

3.2.1.2 Rationale

To date, no LCA study has been conducted on any transportation mode in Mexico City, much less a three-way comparison of three distinct transportation alternatives. Furthermore, once the case study of the comparison between the three modes is completed, the simulation results form the basis of the "stand-alone" (independent of SIMAPRO) Life-Cycle Inventory model, TransportLifeCAMM. The objective of this spreadsheet-based model is to allow the user(s) to gauge the environmental impacts of these three specific modes (BRT, subway, private vehicle) built in any city or metropolitan area across North America.

3.2.1.3 Commissioner

Self-initiated as part of the research activities necessary for the development of TransportLifeCAMM.

3.2.1.4 Interested party

The stakeholders or interested parties of this study may be Mexico City's local government and its environmental agencies (SEDEMA), transportation agencies (SEMOVI), and Mexico's federal environmental ministry (SEMARNAT) and (INECC). Eventually, research results might be of interest to LCA practitioners, environmental engineering and transportation researchers, universities or research centers and those in charge of public policies. Results from this LCA may be of special interest to "sustainable mobility," "green transportation," "smart city" or similar policies and governmental agencies responsible for implementing them.

3.2.1.5 Practitioner

Alma Angelica Hernandez-Ruiz

3.2.1.6 Scope

This LCA covers the Bus Rapid Transit system of Mexico City, known as Metrobús, as it exists in the present (2018), under the assumption that is essentially the same system as it has been since 2008, the date of its last expansion, from 19.4 kms to 30 kms. This is because since then, the stations, depots and road specifications have remained unchanged, and only the number of buses has increased. Spatially, it covers the “Insurgentes Corridor” on “Avenida de los Insurgentes,” one of the major transit corridors in Mexico City, which transverses the city in a north-south orientation. All inputs accounting for more than one percent of the initial material flow of the subsystems and its components are considered for this study, and the outputs are reported for emissions over a cut-off value of 0.5%. Since this is a research project, and pursuant to the requirements of ISO 14040, its mode of analysis is fully attributional, i.e., all elementary flows are considered in their unit process versions (no “system” generalizations, or “black boxes,” are allowed).

3.2.1.7 Functional Unit

The functional unit for this LCA is the air emissions -and other environmental impacts- per 1 passenger-kilometer traveled. This functional unit enables all systems in this study to be treated as functionally equivalent, and describes their primary function, which is to transport a single person, or passenger, over the distance of one kilometer.

The functional unit also has a time dimension associated with it. For the BRT, this is the lifetime of an average BRT vehicle (an Articulated Bus, as described below), which is considered to be 12 years, since this is both the common experience for Mexico City, although it must be noted it is larger than the average age of 7.2 years reported in the United States (BTS a).

3.2.1.8 System Boundary

As previously explained, the BRT system was divided into the vehicle, energy and infrastructure subsystems. Each of these subsystems was analyzed in its full life cycle: raw materials extraction, manufacturing, distribution, operation and end-of-life (as accounted for in Simapro's landfilling process). This is shown in Figure 3-3 to Figure 3-5. The expanded infrastructure subsystem for the BRT, in that it accounts for the processes and materials that were analyzed for the station and depot modules, as part of the infrastructure subsystem, is presented in Figure 3-6. The expanded diagram of the roadway module for the BRT, which depicts the life cycle of the hydraulic concrete of the dedicated BRT lane, is shown in Figure 3-7.

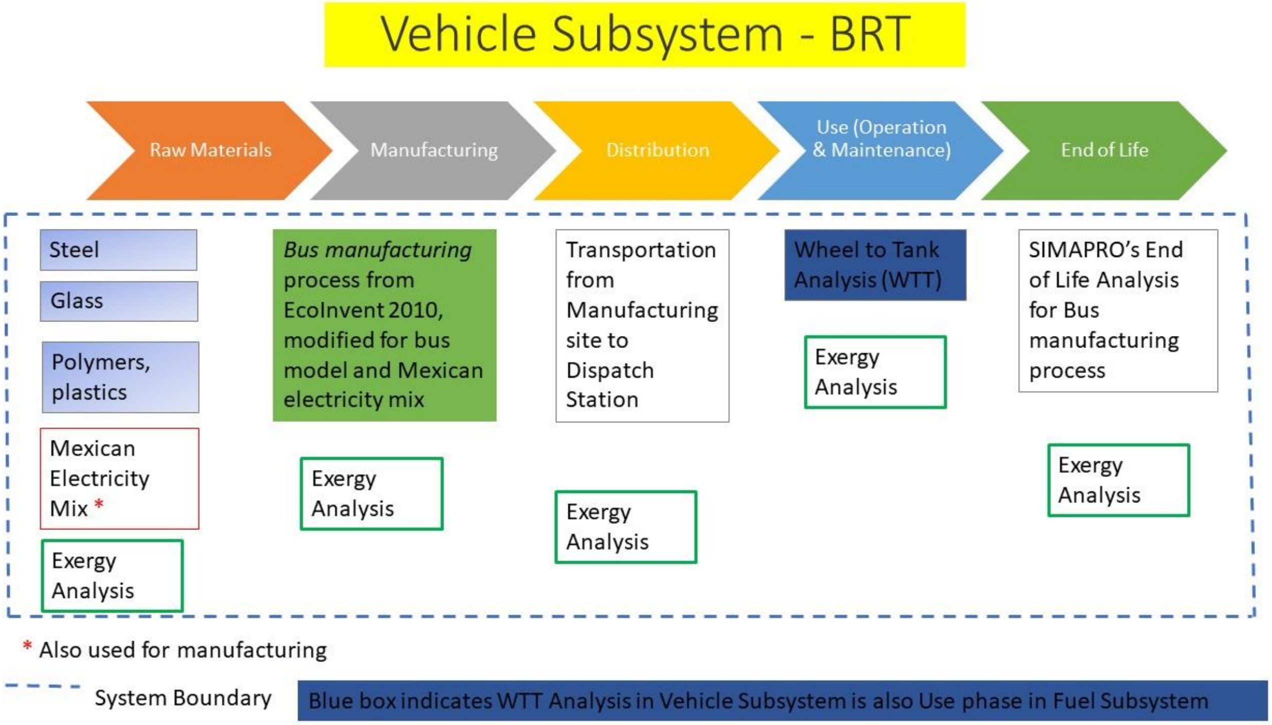

Figure 3-3. Vehicle Subsystem for the BRT (Metrobus) System.

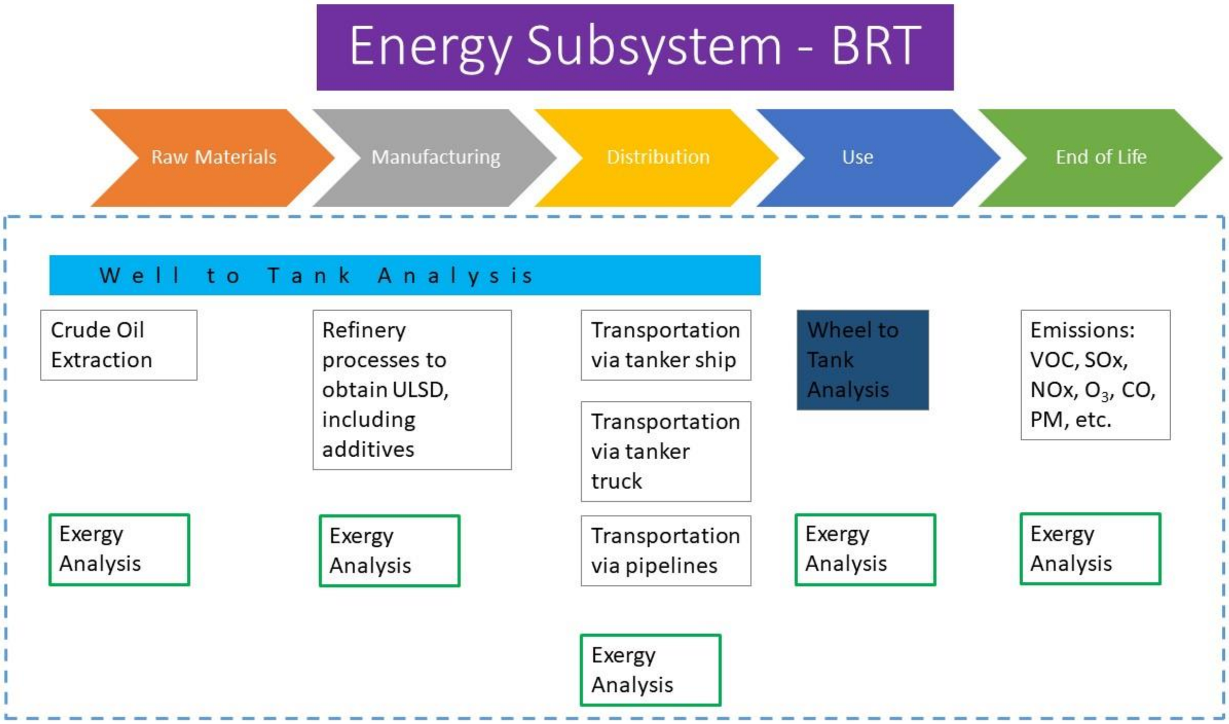

Figure 3-4. Energy Subsystem for the BRT (Metrobus) System.

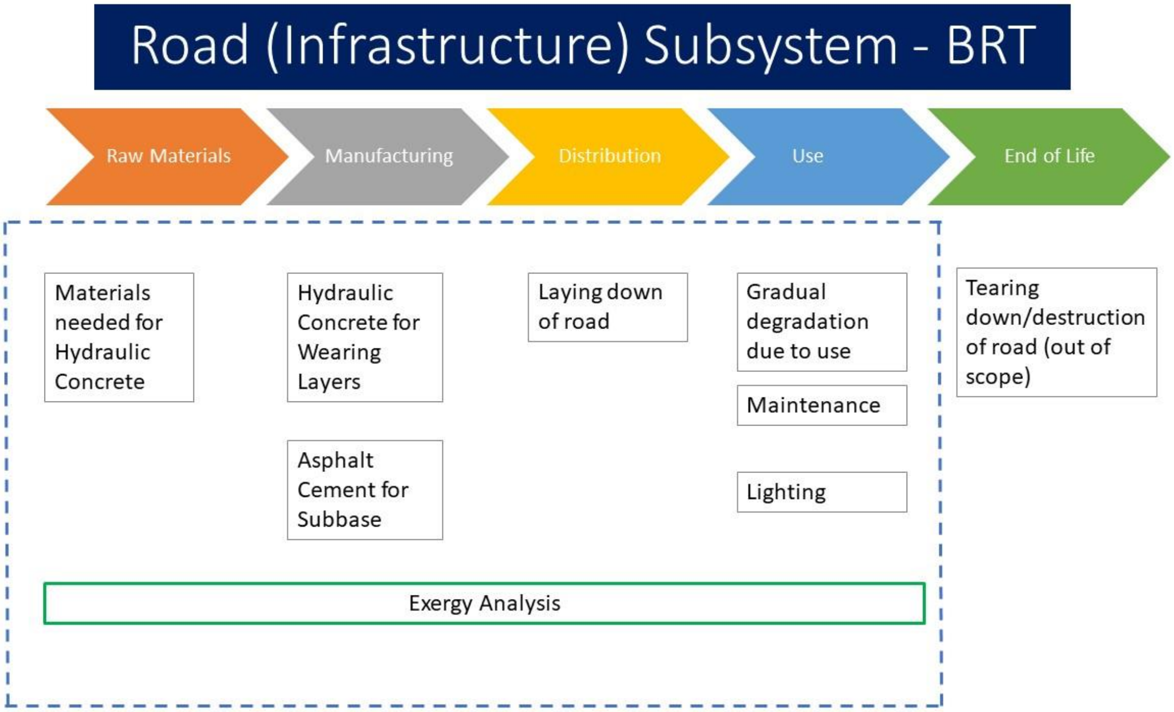

Figure 3-5. Road (Infrastructure) Subsystem for the BRT (Metrobus) System.

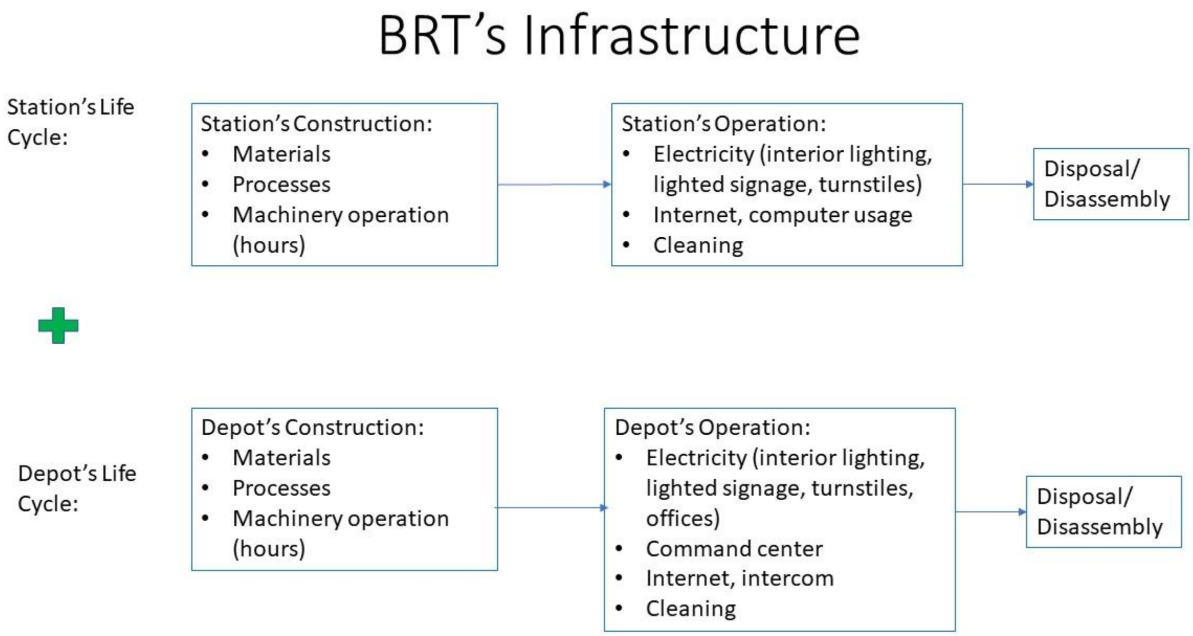

Figure 3-6. Expanded Infrastructure Subsystem for BRT (Metrobus) System.

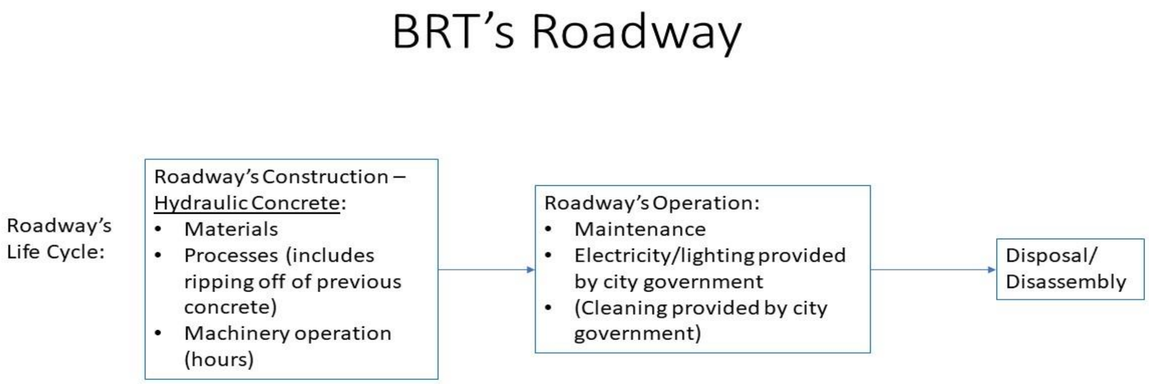

Figure 3-7. Expanded Roadway Module for BRT (Metrobus) System.

3.2.1.9 Geographical Boundary

In the interest of defining a boundary as consistently as possible for the LCA, this dissertation represents the private automobile traveling over the “Avenida de los Insurgentes,” the longest avenue in Mexico City, with a length of 28.8 kilometers (17.9 miles), and the second longest in the world, in a parallel route both to the Metro’s Line 3 and to Line 1 of the Metrobus. Metrobus Line 1 is the red line, running in a north-south direction, in Figure 3-8.

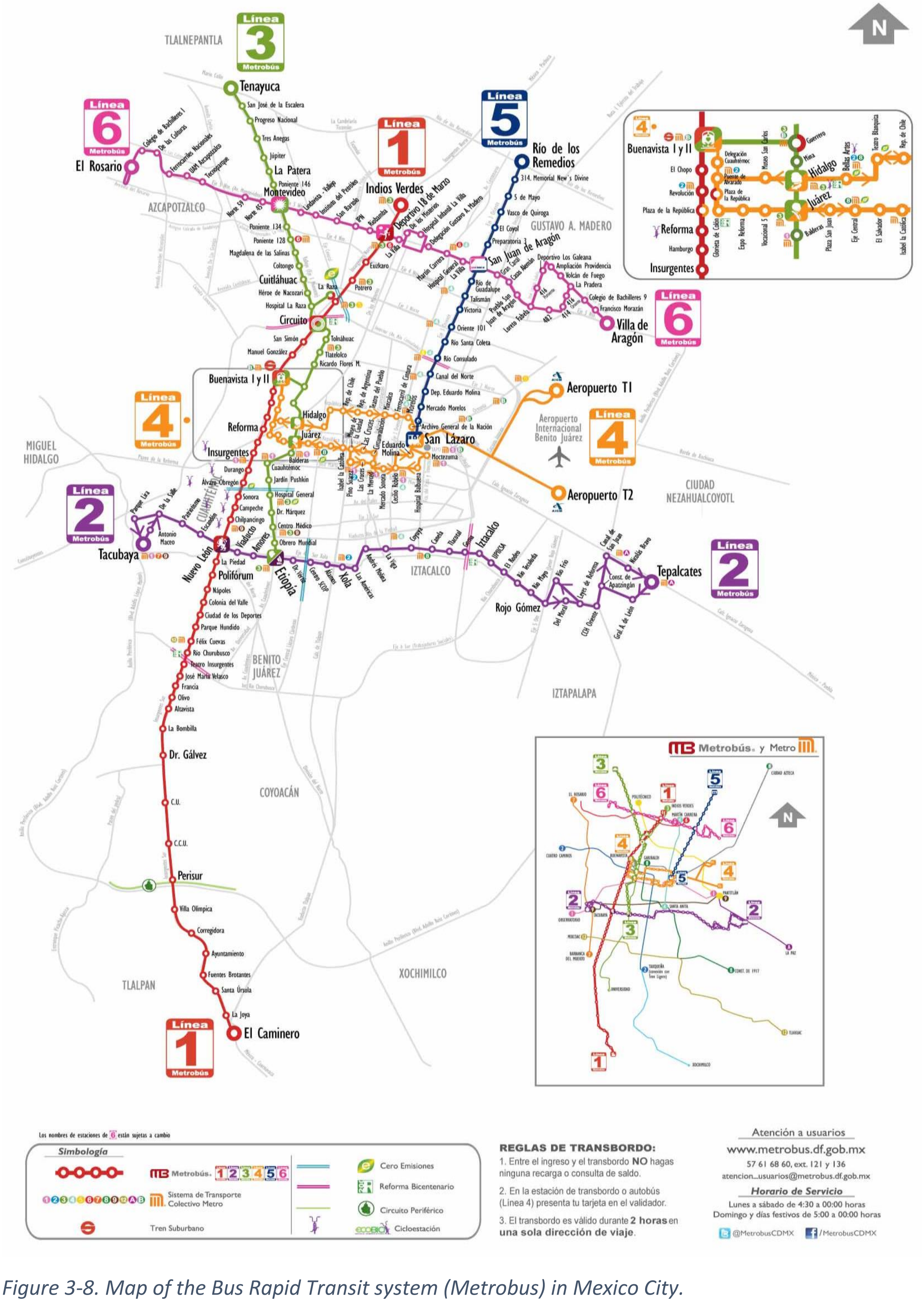

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Figure 3-8. Map of the Bus Rapid Transit system (Metrobus) in Mexico City.

3.2.2 Inventory Analysis

3.2.2.1 System Description

A summary of the several demographic descriptors of Mexico City, relative to its population, land extension, population density and average commute time as of 2015, is presented in Table 3-3.

Table 3-3. Demographic Descriptors of Mexico City.

Mexico City	
Population (2015) [a]	8, 985,339
Land Extension (km^2)	1, 496
Population Density (2015) [a]	5,967.3
Average Commute Time in Car (min) [b]	88

Sources: a. INEGI a (National Institute of Statistics, Geography and Informatics, Mexico). b. Moovit Report, 2016.

Table 3-4 presents the most relevant descriptive characteristics of the BRT System, known as the "Metrobus". Further detail specifically for the line under study, Line 1, is presented in Table 3-5.

As can be seen from data in Table 3-4, Saturday bus ridership is approximately 60%, and Sunday ridership is approximately 40% of weekday demand. These percentages are confirmed by Metrobus reports (Metrobus, Annual Reports, 2011-2017).

It must be noted that the bus ridership reported in Table 3-4 is the listed capacity of the BRT bus, which was used in absence of official data from the Transit Authority. This was considered a reasonable estimate, and in fact, it was the ridership figure used to define a "peak bus," since the saturation of Line 1 buses during peak hours has been observed to be approximately a 25% overflow of listed capacity.

Table 3-4. Characteristics of the Bus Rapid Transit System of Mexico City, Metrobus

Parameter	Value
Bus System Operator (Transit Authority)	System of Public Passenger Transport Corridors in Mexico City (Metrobús)
Bus Fleet Size (January 2017) [c]	565
Bus Fleet Size (January 2017) [c], Line 1	213
Scheduled Daily Bus Service (km) [d]	137,162
Scheduled Daily Bus Service, Line 1 (km)[d]	63,847
Bus Ridership (VKT/PKT)	160 (listed capacity), up to 25% overflow during peak-hour operation
Number of Bus Lines (2018) [d]	7
Number of Bus Routes (December 2017) [d]	20
Average Buses on Weekdays (December 2017) [c]	457
Average Buses on Saturdays, Sundays (December 2017) [c]	295
Average Passengers/day on Weekdays, Line 1 (July 2018)	530,000
Average Age of Fleet (years)[e]	Maximum: 10 years, refurbished:13 years or more
Average Bus Fuel Economy (km/l) [f]	1.1

Sources c. Annual Report 2016, Metrobús. d. Metrobús website, Public Access Records. e. According to Mexico City's "Mobility Law" public transportation vehicles *shall* have a service lifetime of ten years. f. Solís Ávila (2016).

Table 3-5. Characteristics of Line 1, BRT Metrobus in Mexico City.

Line	Path	Routes	Travel kilometers	Cost per kilometer (US Dollar)	Total travel time	Average time from station to station	Daily Passengers
1	Indios Verdes-El Caminero	El Caminero-Indios Verdes	30	0.20	01:22:59	00:01:48	470,000
		Glorieta de Los Insurgentes – Indios Verdes		0.20	00:28:39	00:01:55	
		Buenavista – El Caminero		0.20	01:08:58	00:01:46	
		El Caminero – Buenavista		0.20	01:07:58	00:01:47	
		Dr. Gálvez – Indios Verdes		0.20	01:06:06	00:01:50	
		Tacubaya-Tepalcates		0.30	00:55:59	00:01:40	
		Etiopía – Tepalcates		0.30	00:43:47	00:01:36	

Source: Metrobus, 2017.

To offer some perspective on the overflow and saturation issues that the BRT's Line 1 is already facing, among the top ten stations with the most passengers per day, six are on Line 1 (Metrobus, 2017). The busiest station systemwide is Line 1's depot, Indios Verdes, which reported an average number of 41, 434 passengers per weekday at the Indios Verdes depot, during the first quarter of 2017 (*ibidem*). Other statistics that illustrate Line's 1 challenges, are for example, that with approximately 39% of the system's buses, it carries approximately half the passengers of the Metrobus system (*ibidem*). In a study to rate the BRT system's compliance with the "BRT 2013 Standard" (Morales Vidal, 2015), overflow was in fact the reason why Line 1 did not reach a higher level of compliance than the "Bronze" (lowest) level.

The vehicle chosen for study is the most frequent Articulated Bus in this BRT System, Volvo's "7300 BRT" model (Volvo, 2018). This vehicle has two models: the "Articulated" bus, presented in Figure

3-9, with a listed capacity of 160 passengers, a weight of 30 tons and a length of 18 meters (roughly, 60 feet), and the “Bi-articulated” bus, for 240 passengers, a weight of 40.5 tons and a length of 25 meters, shown in Figure 3-10. Both of these buses are represented with their distinctive red with yellow stripes livery.

Knowing the precise technical specifications for the Articulated and Bi-articulated buses was critical in several ways. First, the “Bus Manufacturing” record in Simapro that was used to model the manufacturing life cycle phase for the buses is based on an 11,000-kilogram bus that is manufactured by Volvo, but at a plant in Germany. This record was scaled up, based on weight, to reflect the 30,000-kilogram 7300 Articulated Volvo bus and the 40,500-kilogram Bi-Articulated Volvo bus. Additionally, the distribution phase of this bus was modified to reflect its manufacturing in Volvo’s manufacturing plant within Mexico City’s Metropolitan Area, at Tultitlán, State of Mexico, 19 kilometers away from the BRT’s depot at “Indios Verdes.” Finally, Mexican electricity was substituted for European one in this record where appropriate.

Figure 3-9. Articulated Bus, Mexico City’s BRT.

Table 3-6 shows the difference in dimensions, listed capacity, curb weight, fuel economy and other characteristics between an average 40-foot BRT bus, and an average 60-foot one.

Figure 3-10. Bi-articulated Bus, Mexico City's BRT

Table 3-6. Comparison of a 40-ft BRT bus versus a 60-ft one.

	40 Foot Standard Bus		**60 Foot Conventional Articulated Bus**		
	Amount	Unit	Amount	Unit	Ratio
Dimensions					
Length	40	ft	60	ft	1.500
Width	102	in	102	in	1.000
Height	116	in	116	in	1.000
Curb Weight	28,500	lbs	66,000	lbs	1.502
Price	$300,000 to $ 340,000	dollars	$525,000 to $725,000	dollars	1.75 - 2.13
Capacity, Floor and Doors					
Seats	40	passengers	41	passengers	1.550
Standees	30	passengers	119	passengers	1.033
Total capacity	70	passengers	160	passengers	1.329
Interior/exterior noise	75/79	dbA	N/A	dbA	
Propulsion and fuel	Diesel or natural gas		Diesel, natural gas or diesel hybrid-electric		
Fuel	ULSD		ULSD		
Fuel Economy	3.3-3.5	mpg	6.091 - 9.32 *	mpg	1.846 - 2.66
Fuel Storage	125	gal	125	gal	1

Daily VKT for an average BRT bus was initially estimated to be 280 km/day, based on the publicly available annual reports (Mexico City Government, Metrobus, 2009 - 2017). However, after examination of the records kept by the Mexican National Institute of Statistics, Geography and Informatics (INEGI b) and own computations based on those records, it was concluded that a better estimate for the average daily distance traveled by a BRT bus was 296 km/day. Similarly, based on a BRT report (Metrobus, 2013) of scheduled maintenance services, it was assumed that each bus is in operation only 300 days/year, to account for maintenance and repairs. Later, this number was updated to 293 days/year, to be in accordance with the figure used both by the INE's study (INE, 2006) and by Embarq's study (2012). Consequently, the BRT's annual VKT was considered to be 86, 728 km/year, with the previously mentioned expected lifetime of 12 years, for a lifetime performance or $VKT_{lifetime}$ = 1'040, 736 km.

As explained in Section 3.1, in order to allocate the impact of any given element of the infrastructure relative to the impact placed upon the entire network, a measurement of the network's performance is needed. For the BRT, the Road's VKT was calculated as follows. Based on the most recently available report (Metrobus, 4th Quarter 2017 Report), the number of buses in Line 1 was reported as 228 buses. With the previously calculated annual VKT for a bus as 86, 728 km, and under the assumption that this figure represents the average vehicle-kilometers traveled for each of the 228 buses currently operating, the road's performance was set as VKT_{ROAD} = 19' 830, 767. 40 km. This is the value by which the impact of each of the infrastructure modules was divided, after it had been multiplied by the respective lifetime ratio and by the number of modules present in the system (Steps 2, 3 and 4 of the methodology explained in Section 3.1). Additionally, in order to ascertain the validity of this number, it was compared against the last known value when the Metrobus system consisted only of Line 1, before it was expanded to include other lines. Since Line 2 of the Metrobus system started operations in December, 2009, we can conclude that the value for Line 1's VKT_{ROAD} is at least of 16, 725,600 km/year, which is the value reported (INEGI b) for the Metrobus system in 2009.Therefore, the assumed value of VKT_{ROAD} = 19’ 830, 767. 40 km in 2018 was deemed adequate.

Regarding the energy subsystem, as mentioned previously, the USLCI database records were used, after being modified and recalculated for the assumptions of this study. The first step in this process was to obtain the detailed spreadsheets for these records directly from NREL. Once this was accomplished, their model assumptions were examined. In the original version, the “Transportation, Transit Bus, Diesel-fueled” record was found to be based on a 16.556 tonnes truck, instead of the 30 metric tons of the Volvo 7300 Articulated bus and the 40.5 metric tons of the Bi-articulated bus used in this study. Moreover, the ridership considered in the original USLCI record was 9.2 passengers, whereas the occupancy in this study is 160 passengers for a peak articulated bus; 90 passengers for an off-peak articulated bus; 240 passengers for a peak bi-articulated bus and 144 passengers for an off-peak bi-articulated bus. It must be noted that in absence of official data from Metrobus, the above occupancies are assumptions, based on perceived occupancies. Hence, the air emissions, as well as the emission rates, were scaled by weight in all cases. Furthermore, the occupancy value was replaced with those mentioned above. Consequently, new values for the passenger*kilometers traveled per 1,000 liters of diesel were obtained, as well as new values for emission rates in grams (of pollutant) per passenger*kilometer.

Table 3-7 presents a summary of these newly recalculated values. The next step was to amend the actual process records within Simapro (which contained the USLCI database), by making a copy of the original records, and then editing them with these new values. Simulations in Simapro were then run using these edited records.

Table 3-7. Modified Emission Rates for Articulated and Bi-articulated BRT bus, peak and off-peak.

	Biarticulated Bus, Off-peak, R = 144		***Biarticulated Bus, Peak, R = 240***		***Articulated Bus, Peak, R = 160***		***Articulated Bus, Off-Peak, R = 90***	
	Value	**Units**	**Value**	**Units**	**Value**	**Units**	**Value**	**Units**
Transport, transit bus, diesel per 1000 L of fuel Air Emissions	459,020	p-km	765,033	p-km	510,022	p-km	286,887	p-km
Name	Modified Value	Units	Modified Value	Units	Modified Value	Units	Modified Value	Units
Ammonia	85.79836744	g	85.79836744	g	63.55434625	g	63.55434625	g
Carbon dioxide, fossil	5751158.173	g	5751158.173	g	4260117.166	g	4260117.166	g
Carbon monoxide, fossil	20983.58337	g	20983.58337	g	15543.39509	g	15543.39509	g
Hydrocarbons (other than methane)	3237.570923	g	3237.570923	g	2398.200684	g	2398.200684	g
Methane	90.16626808	g	90.16626808	g	66.7898282	g	66.7898282	g
Nitrogen dioxide	4444.681022	g	4444.681022	g	3292.356313	g	3292.356313	g
Nitrogen oxide	51226.21468	g	51226.21468	g	37945.34421	g	37945.34421	g
Nitrogen oxides	55670.89605	g	55670.89605	g	41237.70078	g	41237.70078	g
Nitrous oxide	12.86110888	g	12.86110888	g	9.52674732	g	9.52674732	g
Particulates, < 2.5 um	2697.700396	g	2697.700396	g	1998.29659	g	1998.29659	g
Particulates, < 2.5 um, tirewear	11.63970952	g	11.63970952	g	8.622007053	g	8.622007053	g
Particulates, < 2.5 um, brakewear	43.06915755	g	43.06915755	g	31.90307967	g	31.90307967	g
Particulates, < 10 um	2781.03284	g	2781.03284	g	2060.024326	g	2060.024326	g
Particulates, < 10 um, tirewear	48.53755353	g	48.53755353	g	35.95374335	g	35.95374335	g
Particulates, < 10 um, brakewear	164.5242019	g	164.5242019	g	121.8697792	g	121.8697792	g
Sulfur dioxide	91.28888035	g	91.28888035	g	67.62139285	g	67.62139285	g
VOC, volatile organic compounds	3317.49902	g	3317.49902	g	2457.406681	g	2457.406681	g
Average gross vehicle weight (tonnes)	36.74		36.74		27.22		27.22	
*Compared with original weight of 16.566 tonnes, this is a factor of	2.219		2.219		1.644		1.644	

The calculations for the infrastructure subsystem, specifically for the Station and Depot modules, was aided by architectural drawings for both a prototypical BRT station, and for its main depot, the “Indios Verdes” depot located at the North end of Line 1, and almost at the northernmost point for the state of Mexico City. These architectural drawings are presented in Figure 3-11 and Figure 3-12.

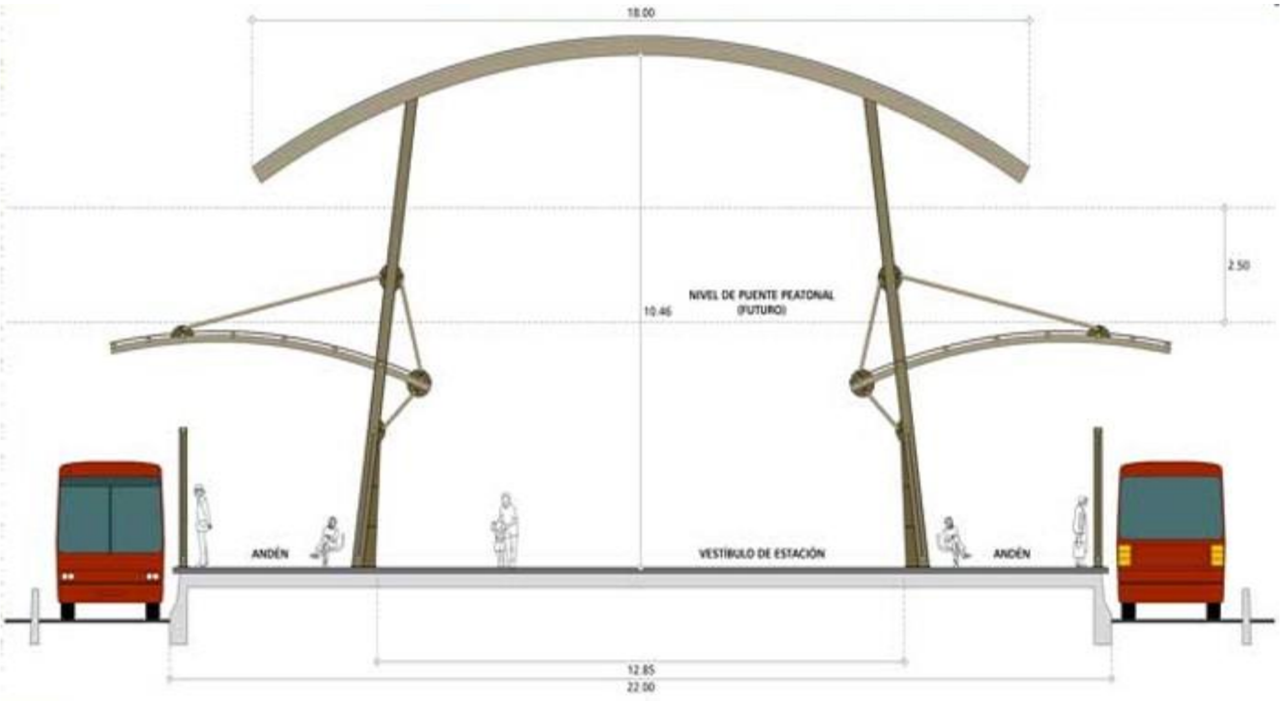


Figure 3-11. Architectural rendition of BRT’s Depot, “Indios Verdes."

Additionally, the “Manifestation of Environmental Impact” for Line 6 of the Metrobus, built during 2015 and inaugurated on January, 2016, was obtained (MIA Line 6, 2016). Although much construction data was missing and there were several important contradictions and typographical errors in that study, it nonetheless proved useful to give a sense of the relative amounts of construction materials, resources and equipment that were probably employed in the construction of Line 1. This was considered a valid hypothesis, particularly since Line 6 replicated the same modular design for the stations and depots, and was also built by the same contractor as Line 1.

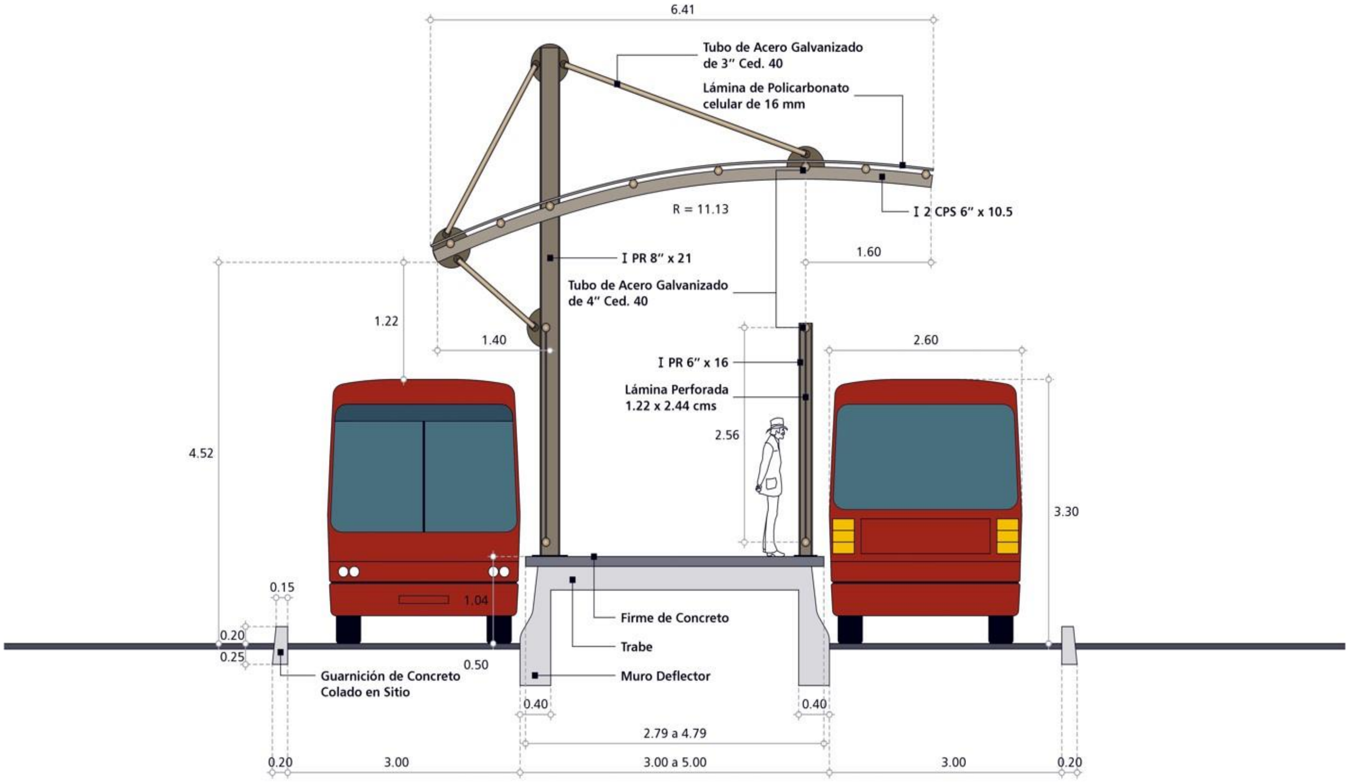


Figure 3-12. Architectural Rendition of a BRT Station.

Station and depot construction activities modelled in this study include: excavation for station foundations, cement mixing and concrete pouring, laying of structural steel elements, laying of tempered glass panes, painting, construction of polycarbonate sheet-based roofing, installation of power supply and internet connectivity.

Materials employed during station and depot construction include: water, cement, sand, gravel (colloquially known as "tepetate"), steel rebars, stirrups and steel wire for ties, structural steel and piping, paint, polycarbonate sheets, tempered glass panes, granite coverings for station walls, lamps, wiring for power supply, fiber optic cable for internet connectivity, turnstiles, internet modems, CCTV cameras for surveillance, acrylic signs, and a satellite/antenna receiver for internet connection.

Table 3-8 to Table 3-10 show the hours of operation, based on the production capacity of earthmoving and other construction equipment that were required for the building of the infrastructure subsystem. These hours were calculated based on the production capacity determined for each earthmoving equipment as explained in Section 3.1.

It is important to note that in a first instance, these hours of operation for the machinery were calculated under three scenarios. In the first scenario, the production capacity of the average model of any particular type of earthmoving equipment was calculated. In the second scenario, twice as many hours were calculated for the same average equipment. Lastly, in the third scenario, the production capacity of the largest available model for each type of equipment was calculated.

Although all this information was computed, eventually it was decided that the average model and its respective operating hours was a close enough representation of actual conditions; therefore, only "Scenario 1" hours of operation were used throughout the Simapro simulations.

Table 3-8. Hours of Operation for Construction Equipment, Station for BRT.

Type of Equipment/Machinery (task)	**Scenario 1 (hours)**	**Scenario 2 (hours)**	**Scenario 3 (hours)**
Excavator	1.00	2.00	1.00
Loaders	8.00	16.00	3.00
Dump Truck	4.00	8.00	2.00
Crane (for roof)	3.00	6.00	2.00
Concrete mixer truck	64.00	128.00	64.00
16-ft^3 mixer	4.00	8.00	4.00

Scenario 1 = Average Model, all equipment

Scenario 2 = Average Model, twice as many operating hours

Scenario 3 = Largest-available Model, all equipment

Table 3-9. Hours of Operation for Construction Equipment, Depot for BRT.

Type of Equipment/Machinery (task)	**Scenario 1 (hours)**	**Scenario 2 (hours)**	**Scenario 3 (hours)**
Excavator	7.00	14.00	3.00
Loaders	39.00	78.00	14.00
Dump Truck	18.00	36.00	6.00
Crane (for roof)	11.00	22.00	11.00
Concrete mixer truck	344.00	688.00	344.00
16-ft^3 mixer	6.00	12.00	6.00

Scenario 1 = Average Model, all equipment

Scenario 2 = Average Model, twice as many operating hours

Scenario 3 = Largest-available Model, all equipment

Table 3-10. Hours of Operation for Construction Equipment, Road for BRT, 30 kms.

Type of Equipment/Machinery (task)	**Scenario 1 (hours)**	**Scenario 2 (hours)**	**Scenario 3 (hours)**
Bulldozers (move construction material)	218.00	436.00	70.00
Bulldozers (move excavated material)	122.00	244.00	39.00
Bulldozers (felling trees; vegetation removal)	63.00	126.00	51.00
Bulldozers (as Rippers)	195.00	390.00	153.00
Total hours of bulldozer work	598.00	1196.00	313.00
Graders	182.00	364.00	188.00
Loaders	2,030.00	4,060.00	752.00
Excavator	363.00	726.00	160.00
Compactor	370.00	740.00	268.00
Dump Truck	1000.00	2000.00	292.00
Scrapers	435.00	870.00	400.00

Scenario 1 = Average Model, all equipment

Scenario 2 = Average Model, twice as many operating hours

Scenario 3 = Largest-available Model, all equipment

It must be highlighted that while the initial calculations for stations and depots were based on the preceding architectural drawings, ultimately, they were verified against the APTA's Recommended Practice for Bus Rapid Transit Stations and Stops (APTA, October, 2010).

As mentioned in Section 3.1.2.2, Simapro variables, known as parameters, were declared within the software to aid in the computation of different product assemblies, or stages. Table 3-11 shows the list of input and calculated parameters for the bus system. The values shown in this table correspond to the base scenario: a peak bus with 160 passengers, traveling 296.85 km daily, in operation 293 days/year, on Line 1 as it is currently, with 30 km of road, 44 stations and 3 depots, expected to last 25 years. The expected lifetime of the road's hydraulic concrete is 20 years.

Table 3-11. Simapro input and calculated parameters for the BRT system.

Input parameters	
NumberofBuses	228
Ridership	160
NumberofStations	44
NumberofDepots	3
VKTdaily	296.85
DaysOperationPerYear	293
BusLifetime	12
RoadLifetime	20
DepotLifetime	25
StationLifetime	25
RoadLength	30
Calculated parameters	
VKTAnnual	VKTdaily*DaysOperationPerYear
VKTLifetime	VKTAnnual*BusLifetime
PKTLifetime	VKTLifetime*Ridership
Station_BusLifetimeRatio	BusLifetime/StationLifetime
Road_BusLifetimeRatio	BusLifetime/RoadLifetime
Depot_BusLifetimeRatio	BusLifetime/DepotLifetime

Table 3-12 lists the materials and processes that were input into Simapro to model the construction of the BRT station, while Table 3-13 lists the inputs for the BRT's depot.

Table 3-12. Input materials and processes for Station's Construction, BRT.

Materials/assemblies	Amount	Units	Comments
Cement, Portland {RoW}| market for | Alloc Rec, U	(287.58*NumberofStations)*Station_BusLifetimeRatio	ton	3.150 tons to a m3
Sand {GLO}| market for | Alloc Rec, U	(766.11*NumberofStations)*Station_BusLifetimeRatio	ton	Density = 1680 kg/m3
Gravel, round {GLO}| market for | Alloc Rec, U	(1279.55*NumberofStations)*Station_BusLifetimeRatio	ton	Density = 1865 kg/m3
Water, deionized, from tap water, at user {GLO}| market for | Alloc Rec, U	(147898.2*NumberofStations)*Station_BusLifetimeRatio	kg	Density = 1000 kg/m3
Natural stone plate, polished, at regional storage/US* US-EI U	(10773*NumberofStations)*Station_BusLifetimeRatio	kg	Width of 0.03 m; granite's density = 2700 kg/m3
PMMA sheet E	(588*NumberofStations)*Station_BusLifetimeRatio	kg	Width =0.01m; PMMA's density =1.20 g/cm3
Polycarbonate, at plant/US- US-EI U	(14851.2*NumberofStations)*Station_BusLifetimeRatio	kg	Density = 1190 kg/m3
Flat glass, coated {GLO}| market for | Alloc Rec, U	(575.99*NumberofStations)*Station_BusLifetimeRatio	kg	Width=0.002 m; density = 2,270kg/m3
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, U	(34.563*NumberofStations)*Station_BusLifetimeRatio	ton	
Chromium steel pipe {GLO}| market for | Alloc Rec, U	(19.80*NumberofStations)*Station_BusLifetimeRatio	ton	
Galvanized steel sheet, at plant/RNA	(394.24*NumberofStations)*Station_BusLifetimeRatio	kg	
Electrostatic paint {GLO}| market for | Alloc Rec, U	(37.84*NumberofStations)*Station_BusLifetimeRatio	kg	Density = 0.88 kg/l
Reinforcing steel {GLO}| market for | Alloc Rec, U	(8*NumberofStations)*Station_BusLifetimeRatio	ton	
Steel, unalloyed {GLO}| market for | Alloc Rec, U	(6.125*NumberofStations)*Station_BusLifetimeRatio	kg	2.5mm steel wire has weight of 0.038759 kg/m
Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S	(8*NumberofStations)*Station_BusLifetimeRatio	ton	
Processes	Amount	Units	Comments
Excavation, hydraulic digger {RoW}| processing | Alloc Rec, U	(332.5*NumberofStations)*Station_BusLifetimeRatio	m3	
Loader operation, large, INW NREL/RNA U	(8*NumberofStations)*Station_BusLifetimeRatio	hr	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(4*NumberofStations)*Station_BusLifetimeRatio	hr	Dump Trucks
Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Alloc Rec, U	(3*NumberofStations)*Station_BusLifetimeRatio	hr	Crane

Table 3-13. Input materials and processes for Depot's Construction, BRT.

Materials/assemblies	Amount	Units	Comments
Cement, Portland {RoW}| market for | Alloc Rec, U	(1550.02*NumberofDepots)*Depot_BusLifetimeRatio	ton	3.150 tons to a m3
Sand {GLO}| market for | Alloc Rec, U	(4129.24*NumberofDepots)*Depot_BusLifetimeRatio	ton	Density of sand = 1680 kg/m3
Gravel, round {GLO}| market for | Alloc Rec, U	(6896.58*NumberofDepots)*Depot_BusLifetimeRatio	ton	Density of gravel = 1865 kg/m3
Water, deionized, from tap water, at user {GLO}| market for | Alloc Rec, U	(797.15*NumberofDepots)*Depot_BusLifetimeRatio	kg	
PMMA sheet E	(76.8*NumberofDepots)*Depot_BusLifetimeRatio	kg	Width =0.01m; PMMA's density =1.20 g/cm3
Polycarbonate, at plant/US- US-EI U	(127330*NumberofDepots)*Depot_BusLifetimeRatio	kg	Density = 1190 kg/m3
Flat glass, coated {GLO}| market for | Alloc Rec, U	(45.7632*NumberofDepots)*Depot_BusLifetimeRatio	kg	Width=0.002m; density = 2270kg/m3
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, U	(73.4*NumberofDepots)*Depot_BusLifetimeRatio	ton	
Chromium steel pipe {GLO}| market for | Alloc Rec, U	(114.27*NumberofDepots)*Depot_BusLifetimeRatio	ton	
Galvanized steel sheet, at plant/RNA	(35.20*NumberofDepots)*Depot_BusLifetimeRatio	kg	
Electrostatic paint {GLO}| market for | Alloc Rec, U	(210.61*NumberofDepots)*Depot_BusLifetimeRatio	kg	Density = 0.88 kg/l
Reinforcing steel {GLO}| market for | Alloc Rec, U	(36.82*NumberofDepots)*Depot_BusLifetimeRatio	ton	
Steel, unalloyed {GLO}| market for | Alloc Rec, U	(30.76*NumberofDepots)*Depot_BusLifetimeRatio	kg	2.55 mm steel wire has weight of 0.038759 kg/m
Processes	Amount	Units	Comments
Excavation, hydraulic digger {RoW}| processing | Alloc Rec, U	(332.50*NumberofDepots)*Depot_BusLifetimeRatio	m3	
Loader operation, large, INW NREL/RNA U	(39*NumberofDepots)*Depot_BusLifetimeRatio	hr	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(18*NumberofDepots)*Depot_BusLifetimeRatio	hr	Dump Trucks
Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Alloc Rec, U	(11*NumberofDepots)*Depot_BusLifetimeRatio	hr	Crane

Once the construction phase for the Station and Depot modules had been calculated, the next step was to estimate the environmental impacts associated with their operation. Station and Depot Operation activities include: station lighting and signaling, as well as power consumption for modem and internet usage, and for lighted commercial signage.

For the construction of the rigid pavement, composed of hydraulic concrete, the following process was followed. Figure 3-13 depicts the usual layer width for hydraulic concrete, as well as those used in this work. These layers were designed following an iterative method, and the final decision as to their widths also considered the rules and regulations set forth both by Mexican federal agencies (SCT, 2013) and the state of Mexico City (Mexico City's Building Code, 2000). Mexico's Communications and Transportation Secretariat (SCT, 2013), in Title 3.01.02, Chapter 26, Hydraulic Concrete, of its "Norms and Procedures for the Conservation and Reconstruction of Highways" establishes that the wearing course (topmost) layer of a hydraulic concrete *shall* be between 25 and 40 cm wide. Further, typical pavement section depths for a rigid pavement are between 8 to 12 inches (175 to 250 millimeters) of Portland cement concrete on a 6-inch (150 millimeter) deep crushed granular base course (*ibid*).

As further confirmation of the appropriateness of these calculations, the answer to a public information request to Mexico City's Public Works and Services Secretariat confirmed that the layer thickness for the hydraulic concrete of the BRT's dedicated lane is indeed in the range between 26 and 32 centimeters (Public Information Request, October, 2018).

For the construction of the BRT's Roadway, no land impact or land use change considerations were taken, since the Avenida Insurgentes was built over streets, rural roads, avenue sections and highways that date to at least the first half of the nineteenth century. Thus, any land use impacts have long ago been assimilated into the surrounding environment.

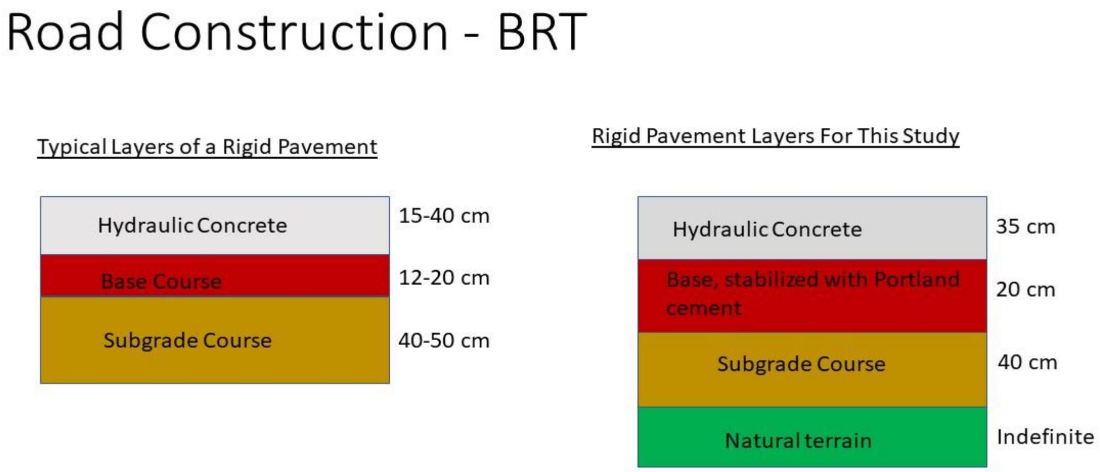


Figure 3-13. Road Design for Hydraulic Concrete, BRT

The activities contemplated for Roadway Construction included: ripper operation to remove previous asphalt, excavation for dedicated lane, laying of hydraulic concrete for dedicated lane, bulldozer operation to haul materials and lay dedicated lane, loader operation, grader operation, compactor operation and dump truck operation, laying of concrete lane dividers.

Materials employed during Roadway Construction include: water, cement, sand, gravel (“tepetate”), concrete, and diesel as fuel for building machinery operation.

Roadway Operation activities include: roadway lighting and signaling.

It should be noted that while in a first instance the roadway’s width was calculated as three meters (3.0 m), upon review of the APTA’s Recommended Practice (APTA, 2010), this width was adjusted to 3.65 m. Table 3-14 presents the road’s dimensions as per the APTA Recommended Practice.

Table 3-14. Cross-section dimensions for BRT's dedicated lane (Source: APTA Recommended Practice APTA-BTS-BRT-RP-003-10, October, 2010).

Description	**Dimension, feet (meters)**		**Notes**
	Preferred	**Constrained**	
BRT/bus lane	12 (3.65 m)	11 (3.35 m)	
Shoulder	4 (1.2 m)	2 (0.6 m)	Wider shoulders suggested for snow storage
Barrier/curb and gutter	2 (0.6 m)	2 (0.6 m)	
Unobstructed vertical clearance over the busway	16.5 (5.0 m)	15.5 (4.7 m)	Clearance allows maintenance and emergency vehicles to utilize the busway. Additionally, future conversion to light rail transit is allowed.
Width of single-lane ramps	14 (4.2 m)		Minimum shoulder for ramp: 4-foot (1.2 m)
Station platform	14 (4.2 m)	12 (3.66 m)	If narrower than 12 feet, must meet ADA requirements

Table 3-15 shows the input materials and processes considered for the road construction, while Table 3-16 lists the processes used for the manufacturing and initial distribution to the BRT bus to the "Indios Verdes" depot. It must be noted that the manufacturing bus process is Simapro's record, which was edited to substitute Mexican electricity, for the global or European average. Furthermore, this record was also scaled up by weight, as previously described, by a factor of 2.73.

3.2.3 Impact Assessment

As explained in Section 3.1, after an initial screening and selection of Environmental Impact Assessment methods, the BEES method was selected for this portion of the LCA study. Results are listed in Chapter 4, Section 4.2.2.

Table 3-15. Input materials and processes for Roadway's Construction, BRT.

Materials/assemblies	Amount	Units	Comments
Cement, Portland {RoW}| market for | Alloc Rec, U	(966*RoadLength)*Road_BusLifetimeRatio	ton	3.150 tons to a m3
Sand {GLO}| market for | Alloc Rec, U	(2572.86*RoadLength)*Road_BusLifetimeRatio	ton	Density of sand = 1680 kg/m3
Gravel, crushed {GLO}| market for | Alloc Rec, U	(2357.9*RoadLength)*Road_BusLifetimeRatio	ton	Cemented gravel for base layer
Gravel, round {GLO}| market for | Alloc Rec, U	(4297.14*RoadLength)*Road_BusLifetimeRatio	ton	Density of gravel = 1865 kg/m3
Water, deionized, from tap water, at user {GLO}| market for | Alloc Rec, U	(496692*RoadLength)*Road_BusLifetimeRatio	kg	
Steel rebar, blast furnace and electric arc furnace route, production mix, at plant GLO S	(82.18*RoadLength)*Road_BusLifetimeRatio	ton	
Processes	Amount	Units	Comments
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(7.26*RoadLength)*Road_BusLifetimeRatio	hr	Bulldozer hours, lumped
Excavation, hydraulic digger {RoW}| processing | Alloc Rec, U	(4453*RoadLength)*Road_BusLifetimeRatio	m^3	
Loader operation, large, INW NREL/RNA U	(67.667*RoadLength)*Road_BusLifetimeRatio	hr	
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(3.333*RoadLength)*Road_BusLifetimeRatio	hr	Dump Trucks
Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Alloc Rec, U	(32.9*RoadLength)*Road_BusLifetimeRatio	hr	Graders, Compactors and Scrapers

Table 3-16. Input processes for Vehicle's Manufacturing and Distribution, BRT

Processes	Amount	Units	Comments
Bus {RoW}| production - Modified for Mexico | Alloc Rec, U	(2.73/VKTLifetime)/Ridership	p	
Transport, combination truck, diesel powered NREL/US U/tkm NREL/RNA U	(570/VKTLifetime)/Ridership	tkm	Manufacturing plant to depot. 19 km * 30 ton, once in bus's lifetime

3.2.4 Interpretation

3.2.4.1 Limitations of Simapro

Although the assumptions for the BRT system were considered to be reasonably reflective of reality, the limitations of Simapro, specifically in its lack of detailed machinery records, did introduce some uncertainty into the system model. Firstly, as Simapro did not have records of building machinery with gasoline as its primary fuel, but only diesel, a generalization had to be made, that all machinery was diesel-powered, an assumption that is from the outset known to be incorrect. Nevertheless, it was the fact that Simapro lacked individual records for graders, compactors and scrapers that led to lumping the operating hours for all these into a single record. Moreover, specific records for bulldozers were similarly unavailable, so the closest possible approximation to this equipment, based on their power rating, was made.

3.2.4.2 Other Assumptions

Since no data was available on the specific characteristics on the concrete used for the construction of the station and depot modules, two scenarios were initially calculated. In the first option, the assumption was made that the concrete was a 3500 PSI concrete, while for the second option it was assumed that a 3000 PSI had been used. Materials necessary for the concrete, i.e., weight of gravel, sand, cement and water, were calculated for both scenarios. Eventually, and upon comparison of the required materials for both scenarios with the list of materials that was available from the Manifestation of Impact Assessment (MIA) of Line 6, it was decided that a 3000 PSI was a better fit. Hence, the materials and processes for the station and depot modules were modeled with a 3000 PSI concrete.

3.3 Methodology for Research Objective 2, Part 2 (Case Study for Mexico City, Private Car)

3.3.1 Goal and Scope Definition

The LCA for a Private Car in Mexico City is an attributional, external study, with a third-order system boundary definition, in that all processes including capital goods (i.e., infrastructure) are considered within the system boundary. However, the capital goods are modeled in a first order model, i.e., only the production of the materials needed to produce the capital goods are included. For this specific LCA, capital goods are considered to be the infrastructure, consisting only of the roadway on which the car is driven.

3.3.1.1 Goal

Perform a traditional LCA of an average, compact-sized private car in Mexico City. Build the life cycle inventory and assess the environmental impacts of the roadway and vehicle subsystems of the Private Car system, throughout the entire life cycle. Ultimately, once the LCA of the Private Car has been concluded, its results will be compared against similarly-conducted LCAs for the subway system of Mexico City and for the BRT. The results of these comparisons will provide the foundation upon which TransportLifeCAMM is built.

3.3.1.2 Reason

To date, no LCA study has been conducted on any transportation mode in Mexico City, much less a three-way comparison of three distinct transportation alternatives. Furthermore, once the case study of the comparison between the three modes is completed, the simulation results form the basis of the "stand-alone" (independent of SIMAPRO) Life-Cycle Inventory model, TransportLifeCAMM. The objective of this spreadsheet-based model is to allow the user(s) to gauge the environmental impacts of these three specific modes (BRT, subway, private vehicle) built in any city or metropolitan area across North America.

3.3.1.3 Commissioner

Self-initiated as part of research activities for the development of TransportLifeCAMM.

3.3.1.4 Interested party

The stakeholders or interested parties of this study may be Mexico City's local government and its environmental agencies (SEDEMA), transportation agencies (SEMOVI), and Mexico's federal environmental ministry (SEMARNAT) and (INECC). Eventually, research results might be of interest to LCA practitioners, environmental engineering and transportation researchers, universities or research centers and those in charge of public policies. Results from this LCA may be of special interest to "sustainable mobility," "green transportation," "smart city" or similar policies and governmental agencies responsible for implementing them.

3.3.1.5 Practitioner

Alma Angelica Hernandez-Ruiz

3.3.1.6 Scope

This LCA represents an average compact (sedan) car in Mexico City, of the best-selling make and model (Nissan Versa). Its operations are modeled in the present (2018), under the assumption that this car and its technology will remain unchanged throughout its lifetime. Spatially, it covers the “Insurgentes Corridor” on “Avenida de los Insurgentes,” one of the major transit corridors in Mexico City, which transverses the city in a north-south orientation. All inputs accounting for more than one percent of the initial material flow of the subsystems and its components are considered for this study, and the outputs are reported for emissions over a cut-off value of 0.5%. Since this is a research project, and pursuant to the requirements of ISO 14040, its mode of analysis is fully attributional, i.e., all elementary flows are considered in their unit process versions (no “system” generalizations, or “black boxes,” are allowed).

3.3.1.7 Functional Unit

The functional unit for this LCA is the air emissions -and other environmental impacts- per 1 passenger-kilometer traveled. This functional unit enables all systems in this study to be treated as functionally equivalent, and describes their primary function, which is to transport a single person, or passenger, over the distance of one kilometer.

The functional unit also has a time dimension associated with it. For the Private Car, this is the lifetime of an average compact vehicle (sedan), which is considered to be 15 years, as that is the reported average car in Mexico City in 2018, down from an average age of 26 years in 2003 (SEMOVI, 2013). It is noted that 15 years is a larger lifetime, although not pointedly so, than the average age of 11.4 years reported in the United States (BTS b).

3.3.1.8 System Boundary

The Private Car system was divided into the vehicle, energy and infrastructure subsystems. Each of these subsystems was analyzed in its full life cycle: raw materials extraction, manufacturing, distribution, operation and end-of-life (as accounted for in Simapro’s landfilling process). This is shown in Figure 3-14 to Figure 3-16. The expanded infrastructure subsystem for the car, accounting for the processes and materials that were analyzed for the roadway, as the lone module of the infrastructure subsystem in this case, is presented in Figure 3-17. The latter figure presents the considerations for the modeling of the flexible pavement, as the asphaltic pavement is generally referred to in Mexico City.

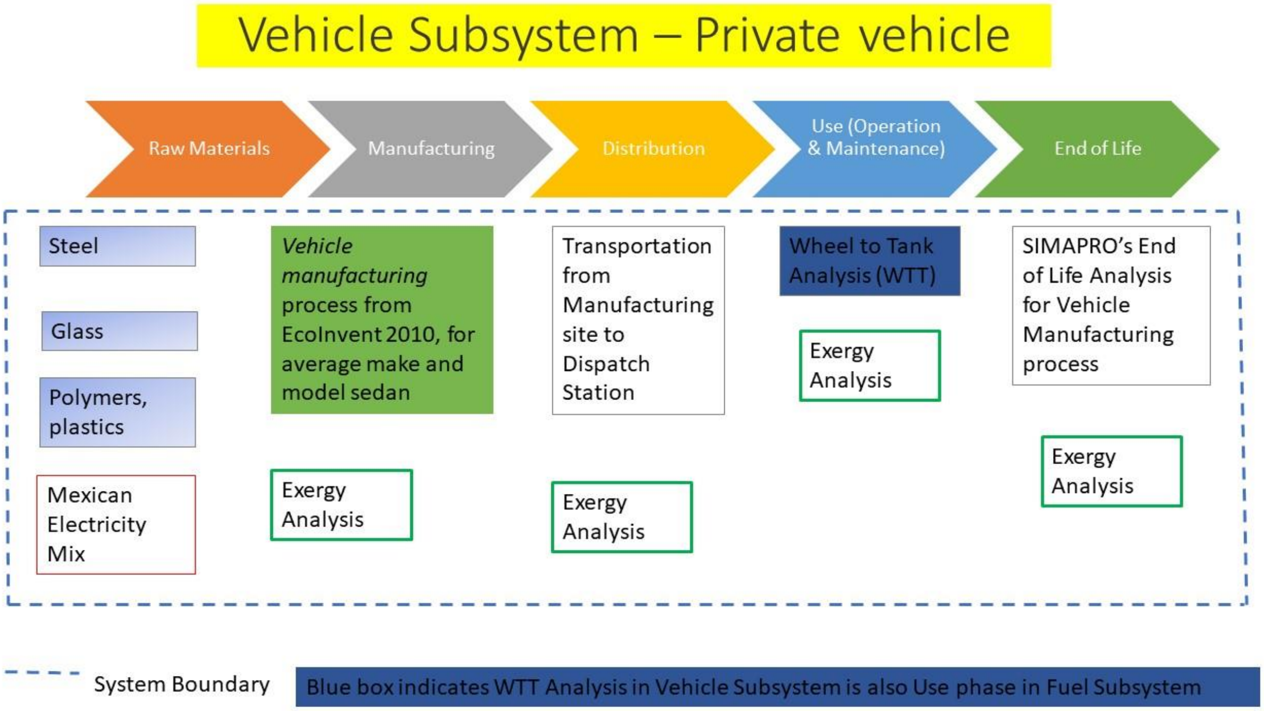


Figure 3-14. Vehicle Subsystem for the Private Car System.

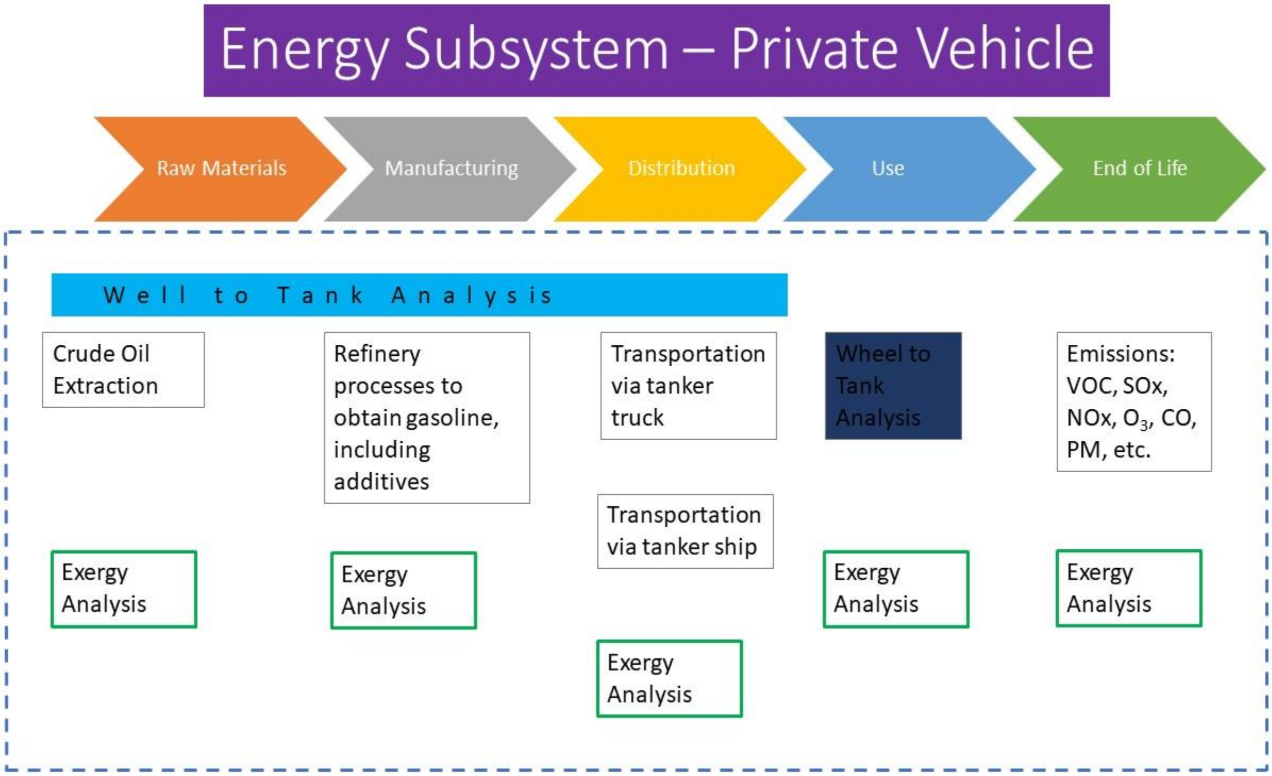


Figure 3-15. Energy Subsystem for the Private Car System.

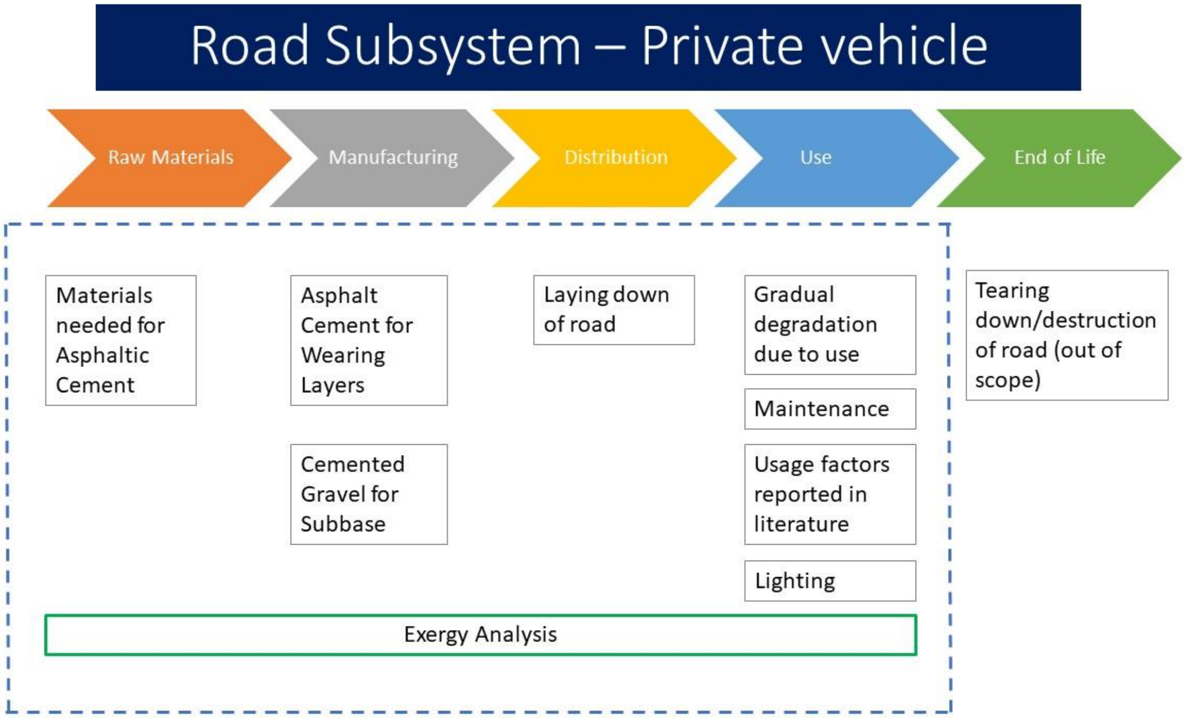


Figure 3-16. Road Subsystem for the Private Car System.

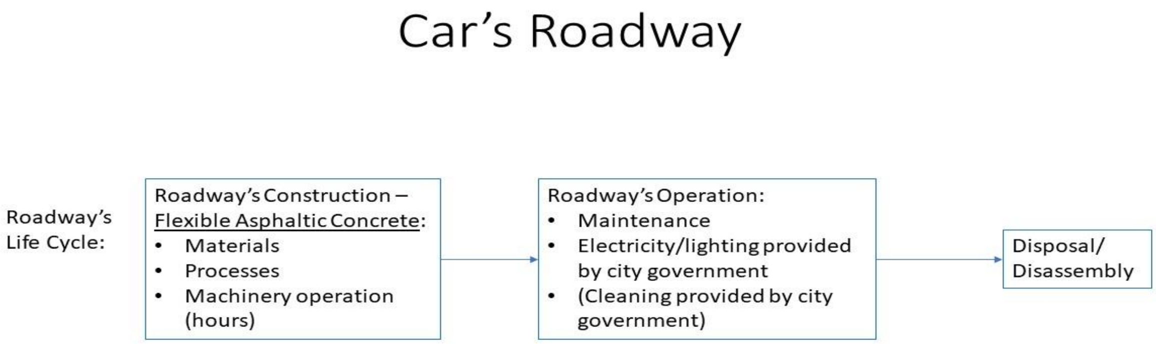


Figure 3-17. Expanded Roadway Module for Private Car System.

3.3.1.9 Geographical Boundary

In the interest of defining a boundary as consistently as possible for the LCA, this dissertation represents the private automobile traveling over the "Avenida de los Insurgentes," the longest avenue in Mexico City, with a length of 28.8 kilometers (17.9 miles), and the second longest in the world, in a parallel route both to the Metro's Line 3 and to Line 1 of the Metrobus. Since the average daily distance traveled by a private car in the Metropolitan Area of Mexico City in the year 2017 is reported as 50 km/day (SEMOVI, *op. cit*.), for the purposes of this LCA, it is assumed that the car travels that distance, although not completely constrained to the geographic extension of "Avenida de los Insurgentes."

3.3.2 Inventory Analysis

3.3.2.1 System Description

The private car chosen for this LCA is an average compact (sedan) car by manufacturer and model: a 5-year old, Nissan Versa 2013. This is the bestselling car in the Metropolitan Area of Mexico City and in Mexico (Expansion, 2017). It is also the most frequent choice for taxi cars. Its maximum passenger capacity is 5 persons (NISSAN, 2013). It has a gross maximum weight of 1474 kg (3250 lbs). The fuel tank's capacity is 41 liters. It has a reported fuel economy of 14.6 km/l in the city and of 20.9 km/l on highways, for a combined fuel capacity of 17.4 km/l (*ibid*).

Occupancy for the private automobile in Mexico City had been extensively quoted as 1.2 passengers/vehicle (Metrobus, Annual Reports 2008-2017). Nevertheless, this value was deemed unrealistic and not representative of the demographic characteristics of the Metropolitan Area of Mexico City. The average family has 4.1 members in Mexico City (INEGI d, 2018). While not all family members participate in the daily commute, it is more than likely to expect that one of the parents and the average two children per household will do, resulting in a ridership nearer to 3 passengers. Therefore, a larger, more realistic value of 1.7 passengers for ridership in these vehicles was used, which was confirmed by other publications (Fimevic, 2000). This ridership value is also closer to the United States' ridership of 1.6 persons per automobile (US DoE, 2018).

Concerning the annual VKT for the modeled vehicle in this study, taking the average commute distance of 50 km/day (SEMOVI, *op. cit.*), and assuming a 5-day/week commute, during 50 weeks a year, to account for a 2-week vacation period, the yearly VKT for the car would be 12,500 kilometers. This assumed value is nearly identical to the one in Table 3-17, with the published values for different transportation modes in Mexico. Consequently, an annual VKT of 12,500 kms was set for the Private Car system.

Table 3-17. Average Annual Vehicle-Kilometers Traveled (VKT), by mode, in Mexico.

Vehicle Type	**Average kilometers traveled per year**
Automobile	12,487
Light truck	23,871
Motorcycle	28,835
Taxi	76,650
Urban bus	78,475
Interurban bus	144,540
Urban Heavy Truck	22,922
Interurban Heavy Truck and semi-trailers	52,304

Source: Solís Ávila, J.C. (2016).

With regards to fuel economy, it has been estimated that in the year 2025 the fuel economy for new vehicles will be approximately 16.5 km/L for trucks and 19.2 km/L for subcompact cars, which is a value not too distant from the 21 km/L expected for the United States, according to the International Council on Clean Transportation (ICCT, 2012). In 2025 the average fuel economy for circulating cars in Mexico will be 11.4 km/L (up from its 2013 value of 9.3 km/L) and for 2050 it is expected to reach 19.9 km/L.

In order to compute the VKT_{ROAD} for the Car System, as a means to adequately allocate the impact of any given car upon the road relative to the impact of all cars placed upon the entire roadway, the next procedure was employed. In a manner consistent with Chester (Chester, 2008), an estimate of the annual VKT_{ROAD} was derived by extrapolation from the values reported by the Bureau of Transportation. In Table 1-05, of the National Transportation Statistics Series, the category "Principal arterials, other" was chosen. Since the car's lifetime is projected 15 years into the future, and the VKT_{ROAD} for 2014 was 107,418.449 kms (66,761 miles), extrapolation by Excel's Growth Trend yielded a value of 117, 680 kms (73,139 miles). In absence of any other information from Mexican agencies, this was considered a reasonable estimate, given the number of lanes and traffic generally observed on Insurgentes Avenue. Corroboration of the adequacy of this figure was obtained through unpublished data from traffic counts that were taken for the “Origin-Destination Survey 2017” by the Institute of Engineering of the National Autonomous University of Mexico (GiiTRAL, 2018). These traffic counts revealed the number of cars on Insurgentes at the intersections in the area under study, to be in the order of 3,000 cars, during peak hour. Thus, Insurgentes' classification as a principal arterial road was confirmed, as well as the value obtained for VKT_{ROAD}.

As far as the energy subsystem is concerned, specific information on the average distance traveled from a refinery in Mexico to a representative station in the Metropolitan Area of Mexico City, and other data specific for the manufacturing, transportation and distribution of gasoline within Mexico was unavailable. Nonetheless, this information regarding the gasoline's life cycle was substituted by that found within the GREET model. Since more than 90% of the gasoline currently used in Mexico is imported (PEMEX, 2017), and in a vast proportion, from the United States, it was considered adequate to take the "Wells-to-Pump" information for this study as essentially the same as that of gasoline within the United States.

Similarly, to model the energy subsystem within Simapro, the USLCI database records were once again modified and recalculated for the assumptions of this study. In the detailed spreadsheets for the "Transportation, Passenger Car, Gasoline-fueled" record, the car was a 1.4788 tonnes vehicle. Since the weight of the modeled car for this study was 1.474 metric tons, all emission rates were recalculated by weight and inputted correctly into Simapro. Additionally, the ridership considered in the original USLCI record was 1.59 passengers, whereas the occupancy in this study is 1.7 passengers for the car.

Table 3-18 presents a summary of the recalculated values for ridership values of 1.7 (base case), 5 (maximum occupancy) and 3 (average ridership). A copy of the original process records of the USLCI database within Simapro was made. After that, these records were edited in the software to include the values for the recalculated emission rates, and the simulations run with these edited records.

Table 3-18. Modified Emission Rates for Private Car, with Several Occupancies.

	Car, Ridership = 1.7		***Car, Ridership = 3***		***Car, Ridership = 5***	
	Value	**Units**	**Value**	**Units**	**Value**	**Units**
Emissions for combustion of 1,000 liters of gasoline in a passenger car.	16,616	p-km	29,322	p-km	48,870	p-km
Air Emissions						
Name	Modified Value	Units	Modified Value	Units	Modified Value	Units
Ammonia	266.50	g	266.50	g	266.50	g
Carbon dioxide, fossil	2534647.71	g	2534647.71	g	2534647.71	g
Carbon monoxide, fossil	43313.92	g	43313.92	g	43313.92	g
Hydrocarbons (other than methane)	3718.76	g	3718.76	g	3718.76	g
Methane	144.10	g	144.10	g	144.10	g
Nitrogen dioxide	548.65	g	548.65	g	548.65	g
Nitrogen oxide	4726.04	g	4726.04	g	4726.04	g
Nitrogen oxides	5274.70	g	5274.70	g	5274.70	g
Nitrous oxide	93.54	g	93.54	g	93.54	g
Particulates, < 2.5 um	91.53	g	91.53	g	91.53	g
Particulates, < 2.5 um, tirewear	9.30	g	9.30	g	9.30	g
Particulates, < 2.5 um, brakewear	21.65	g	21.65	g	21.65	g
Particulates, < 10 um	99.40	g	99.40	g	99.40	g
Particulates, < 10 um, tirewear	38.77	g	38.77	g	38.77	g
Particulates, < 10 um, brakewear	82.71	g	82.71	g	82.71	g
Sulfur dioxide	47.14	g	47.14	g	47.14	g
VOC, volatile organic compounds	3812.26	g	3812.26	g	3812.26	g
Average gross vehicle weight (tonnes)	1.4788		1.4788		1.4788	
*Relative to Car of 1,474 kgs, a factor of =	1.106		1.106		1.106	

Table 3-19 shows the hours of operation that were required for the building of the infrastructure subsystem, which in this case contains only the road module. These hours were calculated as explained on section 3.1. Similarly, although three scenarios were calculated for the use of building equipment, ultimately only the operating hours with the production capacity of the average equipment were modeled within the software.

Table 3-19. Hours of Operation for Construction Equipment, Road for Private Car, 50 kms.

Type of Equipment/Machinery (Task)	Scenario 1	Scenario 2	Scenario 3
Asphalt Pavers	442.00	884.00	350.00
Bulldozers (move construction material)	193.00	386.00	37.00
Bulldozers (move excavated material)	193.00	386.00	37.00
Bulldozers - (as Rippers)	160.00	320.00	125.00
Bulldozers - total hours of operation	546.00	1,092.00	199.00
Compactor	217.00	434.00	284.00
Excavator	346.00	692.00	153.00
Graders	302.00	604.00	312.00
Loaders	1,263.00	2,526.00	438.00
Dump Truck	729.00	1,458.00	182.00
Scrapers	231.00	462.00	213.00

Scenario 1 = Average Model, all equipment

Scenario 2 = Average Model, twice as many operating hours

Scenario 3 = Largest-available Model, all equipment

For the infrastructure subsystem (road), the pavement layers of a “flexible” pavement, i.e., an asphaltic were designed as shown in Figure 3-18. It was assumed that this pavement is placed as a hot rolled asphalt. For a flexible pavement, the typical depths are 7 to 8 inches (125 to 175 millimeters) of asphaltic concrete pavement over 12 to 18 inches (300 to 375 millimeters) of crushed granular base course (SCT, 2013). The life cycle of asphalt includes an overlay of 2 inches, with an approximate lifetime of 10 years.

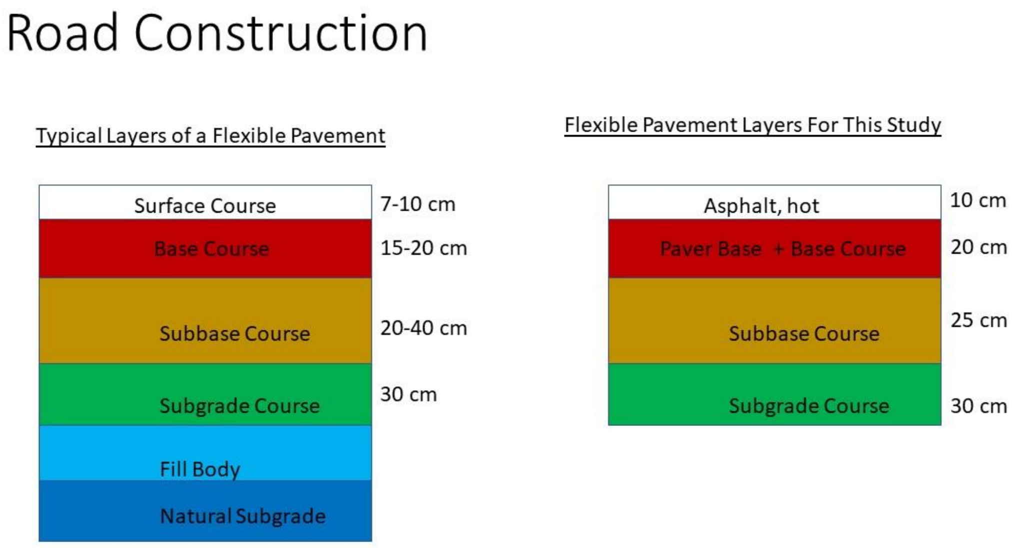


Figure 3-18. Road Design for Flexible Pavement, Private Car.

The road module for the car introduced an extra variable. By conceptually dividing the flexible pavement into upper pavement layers (the wearing course, or asphaltic cover, and the paver base, consisting mostly of sand), and the “lower road” layers (the subgrade, subbase and the base course), two variables, instead of one, were defined for the lifetime of the road. The wearing course’s lifetime is captured in the “RoadLifetime” variable, while the lower layers correspond to the “LowerRoadLifetime” variable. This was done with the intention of establishing a way to model a much faster degradation and replacement for the topmost asphaltic layer of the road than for the rest of the pavement. These two variables are listed in Table 3-20.

Table 3-20.Simapro input and calculated parameters for the Private Car system.

<u>Input parameters</u>	
CarLifetime	15
RoadLifetime	10
LowerRoadLifetime	40
VKTDaily	50
CommutingDaysperYear	250
Ridership	1.7
RoadKm	50
VKTRoad	117,679.9
<u>Calculated parameters</u>	
VKTAnnual	VKTDaily*CommutingdaysperYear
VKTLifetime	VKTAnnual*CarLifetime
Road_CarLifetime	CarLifetime/RoadLifetime
LowerRoad_CarLifetime	CarLifetime/LowerRoadLifetime
PKTLifetime	VKTLifetime*Ridership

Additionally, to ensure that the replacement of the road would be correctly accounted for, the assumption was made that one percent of the road gets replaced every year. This signifies that the road is completely replaced every 100 years. Table 3-21 shows that this road maintenance process was set up in Simapro as a percentage of the assembly that was defined for Road Construction.

Table 3-21. Road Maintenance, Car System.

<u>Materials/assemblies</u>	<u>Amount</u>	<u>Units</u>
Road Construction	0.01*CarLifetime	p

Table 3-22 and Table 3-23 list the materials and processes that were input into Simapro for the Road Construction and for Vehicle Maintenance, respectively.

Table 3-22. Input Materials and Processes for Road Construction, Private Car.

Materials/assemblies	Amount	Units	Comment
Gravel, round {GLO}| market for | Alloc Rec, U	(1174950*RoadKm)*LowerRoad_CarLifetime	kg	70% of Subgrade
Sand {GLO}| market for | Alloc Rec, U	(494370*RoadKm)*LowerRoad_CarLifetime	kg	30% of Subgrade
Cement, Portland {RoW}| market for | Alloc Rec, U	(8268.75*RoadKm)*LowerRoad_CarLifetime	kg	Base
Gravel, crushed {GLO}| market for | Alloc Rec, U	(1215000*RoadKm)*LowerRoad_CarLifetime	kg	Equivalent of Tepetate, Subbase
Sand {GLO}| market for | Alloc Rec, U	(20050.68*RoadKm)*Road_CarLifetime	kg	Paver Base
Bitumen, at refinery/kg/US	(69900*RoadKm)*Road_CarLifetime	kg	Pavement
Water, deionized, from tap water, at user {GLO}| market for | Alloc Rec, U	(4252.50*RoadKm)*LowerRoad_CarLifetime	kg	
Processes	Amount	Units	Comment
Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Alloc Rec, U	(8.84*RoadKm)*Road_CarLifetime	hr	Asphalt Paver
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(10.92*RoadKm)*LowerRoad_CarLifetime	hr	Average Bulldozer, total hours
Excavation, hydraulic digger {RoW}| processing | Alloc Rec, U	(6.92*RoadKm)*LowerRoad_CarLifetime	m3	Average Excavator
Loader operation, large, INW NREL/RNA U	(25.26*RoadKm)*LowerRoad_CarLifetime	hr	Average Loader
Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Rec, U	(14.58*RoadKm)*LowerRoad_CarLifetime	hr	Average Dump Trucks
Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Alloc Rec, U	(15*RoadKm)*LowerRoad_CarLifetime	hr	Average Grader, Compactor and Scrapers

Table 3-23. Input Materials and Processes for Vehicle Maintenance, Private Car.

Materials/assemblies	Amount	Units	Comment
Lubricating oil {GLO}| market for | Alloc Rec, U	62.106	kg	Engine oil. Density lubricating oil = 941 kg/m3; 66 liters = 62.106 kgs
Proxy_Hydraulic fluid, at plant NREL/US U	12.32	kg	Transmission fluid, ATF. Density hydraulic fluid oil = 880 kg/m3; 14 liters =12.32 kgs
Air filter, decentralized unit, 180-250 m3/h {GLO}| market for | Alloc Rec, U	6	p	
Ethylene glycol {GLO}| market for | Alloc Rec, U	19.425	kg	Windshield wiper fluid. Antifreeze, with methanol, for wiper fluid. Density= 1.11 g/cm3.
Synthetic rubber {GLO}| market for | Alloc Rec, U	43.2	kg	Tire. 1 tire = 10 kg;27% synthetic rubber, 14% natural rubber. 14-15% steel
Carbon black {GLO}| market for | Alloc Rec, U	44.8	kg	Tire. 28 %
Reinforcing steel {GLO}| market for | Alloc Rec, U	22.4	kg	Tire
Natural rubber-based sealing, at plant/US** US-EI U	22.4	kg	Tire
Lead {RoW}| treatment of scrap acid battery, remelting | Alloc Rec, U	43.5	kg	Battery. Lead dioxide plates et al. 8.7 kgs of a 14.5 kgs battery is lead.
Dipropylene glycol monomethyl ether {RER}| production | Alloc Rec, U	13.174	kg	Brake fluid. Density = 941 kg/m3. 14 liters = 13.174
Sulfuric acid {GLO}| market for | Alloc Rec, U	29	kg	Battery. Density = 1.84 g/cm3. Approximately 3.15 liters per battery.

Vehicle manufacturing utilized the existing record in Simapro, based on the manufacturing of a Volkswagen Golf A4 (Schweimer and Levin, 2000), scaled up by weight, and with a substitution of European electricity for the Mexican mix, as previously mentioned. This is shown in Table 3-24.

Table 3-24. Vehicle Manufacturing, Car System

Processes	Amount	Unit
Passenger car, petrol/natural gas {GLO}| production, edited for Mexico | Alloc Rec, U	1474	kg

3.3.3 Impact Assessment

After an initial screening and selection of Environmental Impact Assessment methods, the BEES method was selected for this portion of the LCA study. Results are listed in Chapter 4, Section 4.3.2.

3.3.4 Interpretation

3.3.4.1 Limitations of Simapro

The main limitation of the software relative to this LCA was again the lack of specific records for detailed pieces of machinery. Although the hours of operation had been individually calculated, these hours were lumped into a general category. It is considered that while regrettably a certain degree of precision was lost by this lumping together of data, nevertheless this did not have a significant negative effect in the overall data quality, nor eventually on the results of this study.

3.3.4.2 Other Assumptions

It was decided to model the infrastructure subsystem (the road module), and specifically for the cemented gravel portion of the subbase layer, with the materials (cement, water, sand and gravel) more closely resembling a 3000 PSI concrete than any other alternative.

3.4 Methodology for Research Objective 2, Part 3 (Case Study for Mexico City, Subway)

3.4.1 Goal and Scope Definition

The LCA for Mexico City’s Bus Rapid Transit (BRT) is an external study, performed in an attributional mode of analysis. It has a third-order system boundary definition: all processes including capital goods (i.e., infrastructure) are considered within the system boundary. However, the capital goods are modeled in a first order model, i.e., only the production of the materials needed to produce the capital goods are included. For this specific LCA, capital goods are considered to be the roadway and the infrastructure (stations and depot) of the BRT system.

3.4.1.1 Goal

Conduct a traditional LCA of Mexico City's Subway system. Build the life cycle inventory and assess the environmental impacts of the infrastructure (railway, stations and depot), and vehicle subsystems of the Subway system, throughout the life cycle. Ultimately, once the LCA of the Subway system has been concluded, its results will be compared against similarly-conducted LCAs for the BRT system of Mexico City and for a private car. The results of these comparisons will provide the foundation upon which TransportLifeCAMM is built.

3.4.1.2 Rationale

As of this writing, no LCA study has been conducted on any transportation mode in Mexico City, much less a three-way comparison of three distinct transportation alternatives. Furthermore, once the case study of the comparison between the three modes is completed, the simulation results form the basis of the "stand-alone" (independent of SIMAPRO) Life-Cycle Inventory model, TransportLifeCAMM. The objective of this spreadsheet-based model is to allow the user(s) to gauge the environmental impacts of these three specific modes (BRT, subway, private vehicle) built in any city or metropolitan area across North America.

3.4.1.3 Commissioner

Self-initiated as part of the research activities for the development of TransportLifeCAMM.

3.4.1.4 Interested party

The stakeholders or interested parties of this study could be Mexico City's local government and its environmental agencies (SEDEMA), transportation agencies (SEMOVI), and Mexico's federal environmental ministry (SEMARNAT) and (INECC). Eventually, research results might be of interest to LCA practitioners, environmental engineering and transportation researchers, universities or research centers and those in charge of public policies. Results from this LCA could be of special interest to "sustainable mobility," "green transportation," "smart city" or similar policies and governmental agencies responsible for implementing them.

3.4.1.5 Practitioner

Alma Angelica Hernandez-Ruiz

3.4.1.6 Scope

This LCA studies the Subway system of Mexico City, known as Metro, in its Line 3, as it exists in the present (2018), under the assumption that is essentially the same system as it was when it started operations in 1970. Although Line 3 has been expanded five times since its inauguration (in 1978, 1979, twice in 1980 and in 1983), the number of stations, depots and railway specifications have since remained unaltered, and only the number of trains has increased. Spatially, Line 3 starts and follows along the first six kilometers of the “Insurgentes Corridor” on “Avenida de los Insurgentes,” one of the major transit corridors in Mexico City, which transverses the city in a north-south orientation. All inputs accounting for more than one percent of the initial material flow of the subsystems and its components are considered for this study, and the outputs are reported for emissions over a cut-off value of 0.5%. Since this is a research project, and pursuant to the requirements of ISO 14040, its mode of analysis is fully attributional, i.e., all elementary flows are considered in their unit process versions (no “system” generalizations, or “black boxes,” are allowed).

3.4.1.7 Functional Unit

The functional unit for this LCA is the air emissions -and other environmental impacts- per 1 passenger-kilometer traveled. This functional unit enables all systems in this study to be treated as functionally equivalent, and describes their primary function, which is to transport a single person, or passenger, over the distance of one kilometer.

The functional unit also has a time dimension associated with it. For the Subway, this is the lifetime of an average train, which is considered to be 35 years, which is the common experience for Mexico City, although it is more than 30% higher than the average age of 22.8 years for heavy rail passenger cars reported in the United States (BTS a). Nevertheless, in Europe the average operational lifespan is also assumed to be 32 years for most of the Environmental Product Declarations (EPD) reviewed for this work (Bombardier-Alstom, 2015; Ansaldo-Breda, 2011; Siemens, 2014). For reference, the functional unit in the LCAs that gave rise to the aforementioned EPDs was the transportation of 1 passenger over 100 kms, not one kilometer as the present study.

3.4.1.8 System Boundary

Consistent with the methodology expressed in Section 3.1, the Subway system was divided into the vehicle, energy and infrastructure subsystems. Each of these subsystems was analyzed in its full life cycle: raw materials extraction, manufacturing, distribution, operation and end-of-life (as accounted for in Simapro’s landfilling process). This is shown in Figure 3-19 to Figure 3-21. The expanded infrastructure subsystem for the Subway, accounting for the processes and materials that were analyzed for the station and depot modules, as part of the infrastructure subsystem, is presented in Figure 3-22. The expanded diagram of the railway module for the Subway, which depicts the life cycle of the Subway track, is shown in Figure 3-23.

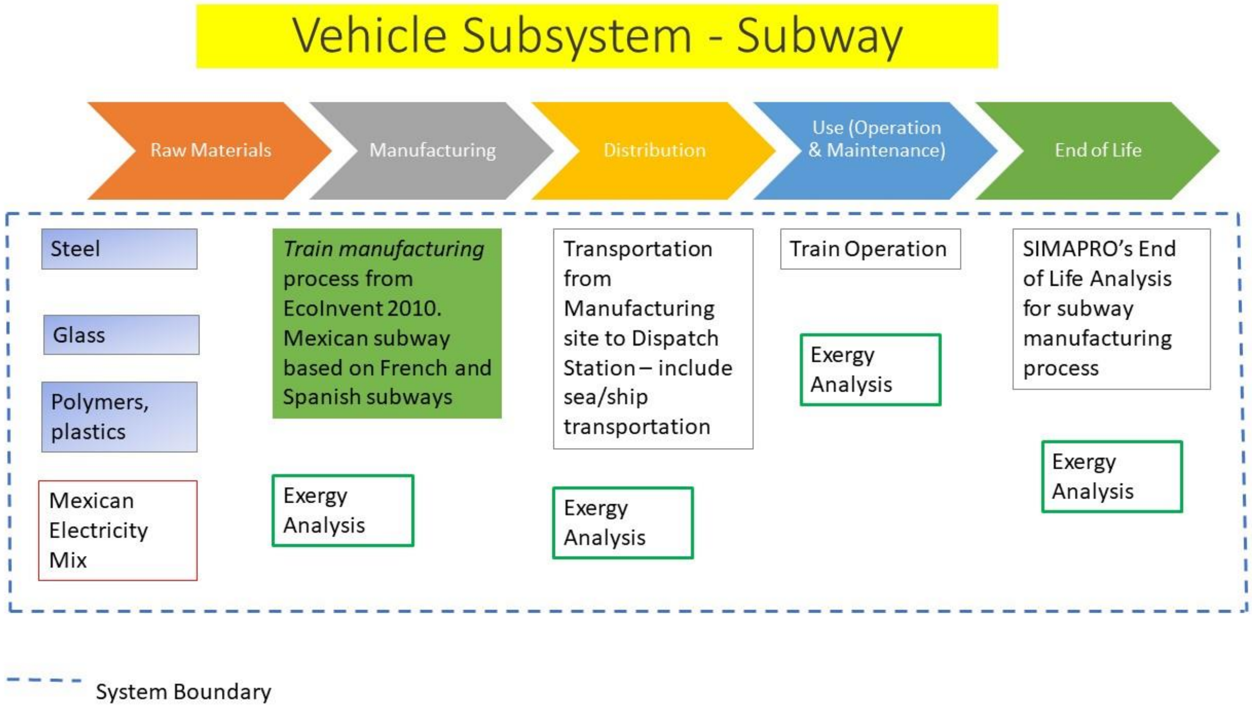


Figure 3-19. Vehicle Subsystem for the Subway (Metro) System.

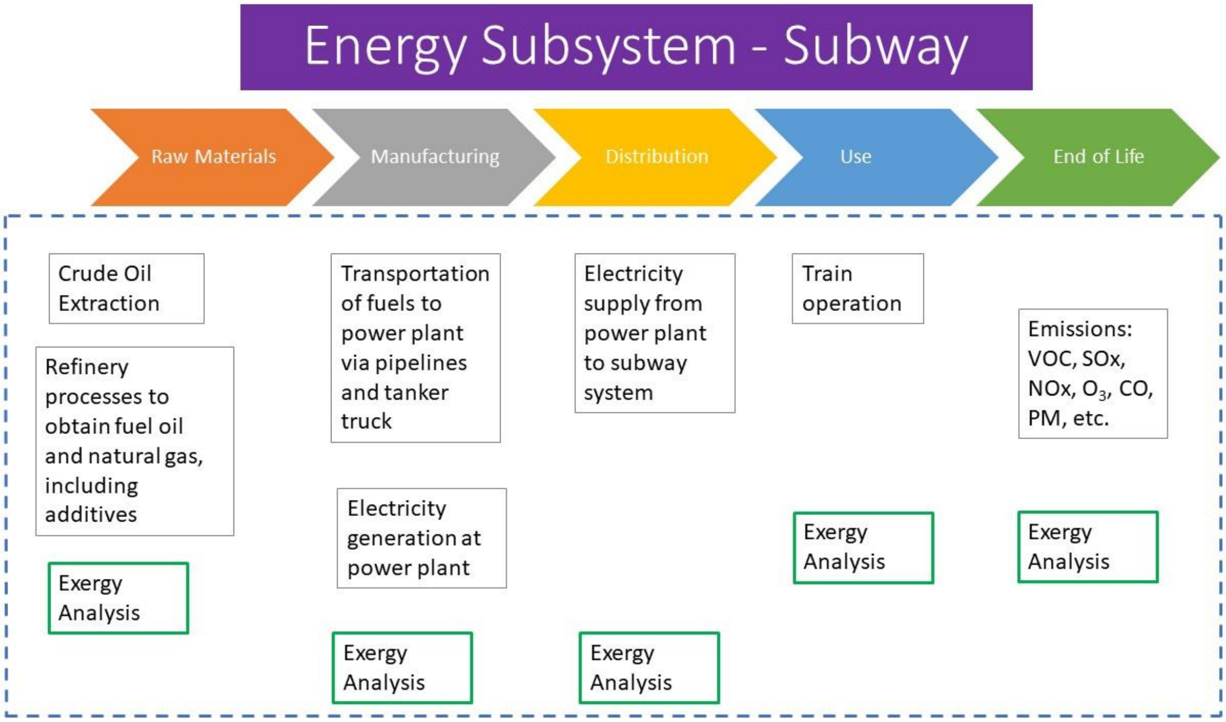


Figure 3-20. Energy Subsystem for the Subway (Metro) System.

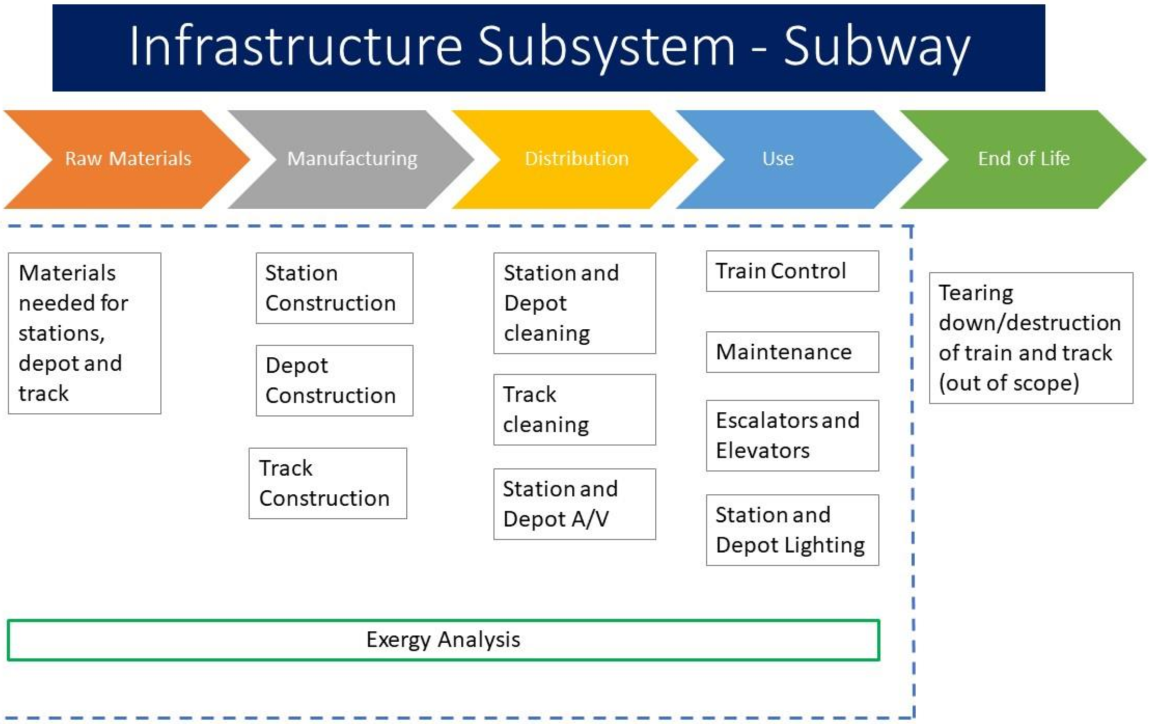
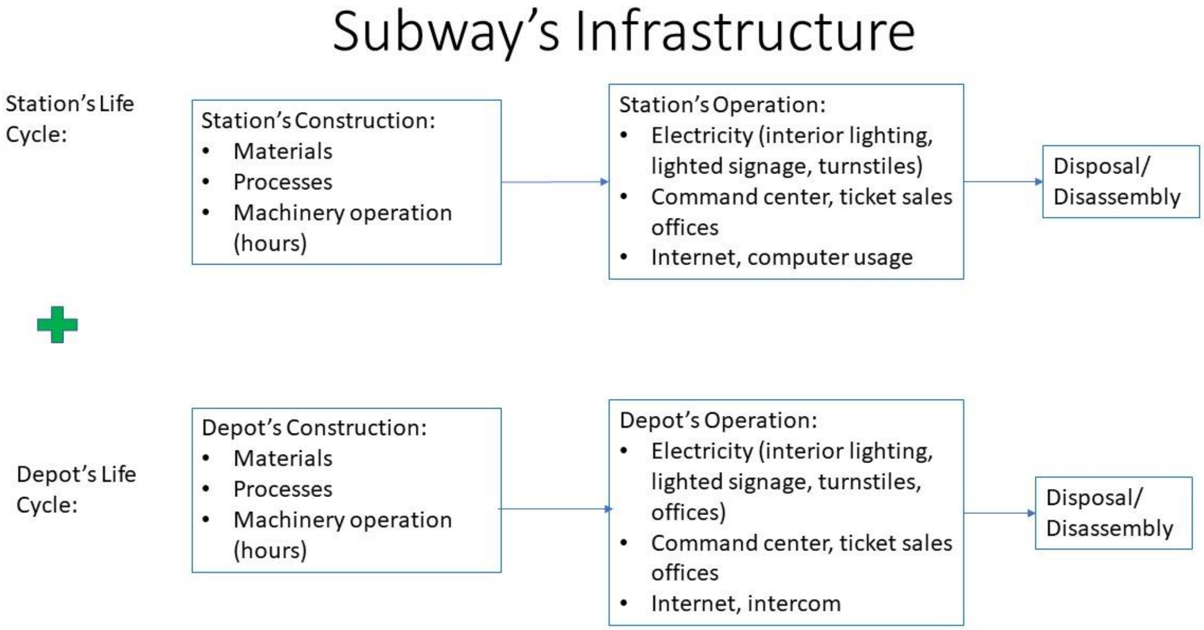


Figure 3-21. Infrastructure Subsystem for Subway (Metro) System.



Subway’s Infrastructure

Station’s Life Cycle:

Station’s Construction:
- Materials
- Processes
- Machinery operation (hours)

Station’s Operation:
- Electricity (interior lighting, lighted signage, turnstiles)
- Command center, ticket sales offices
- Internet, computer usage

Disposal/ Disassembly

✚

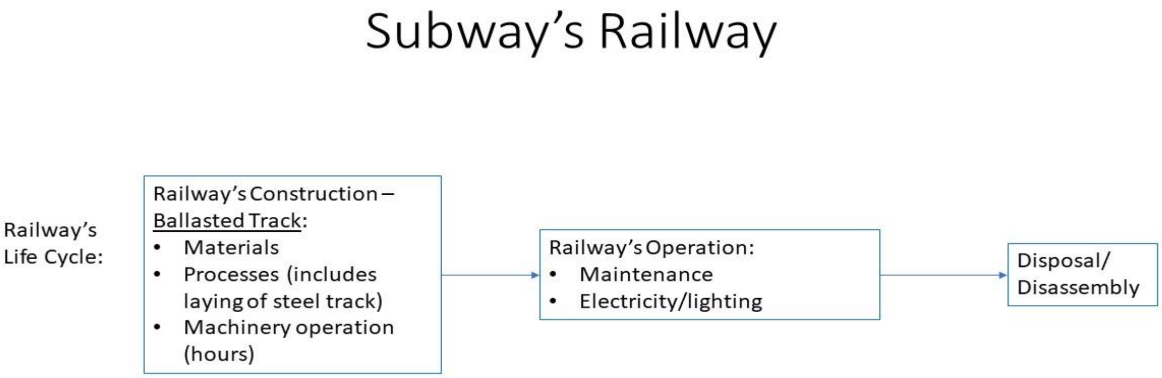
Depot’s Life Cycle:

Depot’s Construction:
- Materials
- Processes
- Machinery operation (hours)

Depot’s Operation:
- Electricity (interior lighting, lighted signage, turnstiles, offices)
- Command center, ticket sales offices
- Internet, intercom

Disposal/ Disassembly

Figure 3-22. Expanded Infrastructure Subsystem for Subway (Metro) System.



Subway’s Railway

Railway’s Life Cycle:

Railway’s Construction – <u>Ballasted Track</u>:
- Materials
- Processes (includes laying of steel track)
- Machinery operation (hours)

Railway’s Operation:
- Maintenance
- Electricity/lighting

Disposal/ Disassembly

Figure 3-23. Expanded Railway Module for Subway (Metro) System.

3.4.1.9 Geographical Boundary

To define a consistent boundary, this dissertation represents a subway train of Mexico City's Line 3, which in its first six kilometers is parallel to the "Avenida de los Insurgentes," the longest avenue in Mexico City, with a length of 28.8 kilometers (17.9 miles), and the second longest in the world. The subway's (Metro) Line 3 is the grass-green line, running in a north-south direction, in Figure 3-24.

Figure 3-24. Map of the subway system (Metro) in Mexico City.

3.4.2 Inventory Analysis

3.4.2.1 System Description

Mexico City's Subway System, the first to be built in Latin America, is the transportation mode of choice for approximately 19% of commuters (GiiTRAL, 2018). While it has been advertised and promoted as the "zero-emissions" transportation alternative, that is quite naturally, untrue. The fact that there are no visible emissions associated with it onsite does not discount the fact that these emissions are certainly present at the distant power stations where the electricity is generated. Particularly from a whole life-cycle viewpoint, it is good to remember this.

Table 3-25 presents some relevant characteristics of the subway. It must be noted that while some sources quote the subway as the transportation option for 14% of the trips (UN Habitat, 2015), other claim this percentage is closer to 19% (GiiTRAL, 2018).

Table 3-25. Characteristics of Subway, "Collective Transportation System, STC" Metro.

Public Transportation managed by Mexico City's Government (STC Metro).	
Covers 14 % of demand	2,800,000 Trips
Lines	11
Stations	175
Kilometers with double railways	201
Trains	308
Passengers	4,200,000 Passengers/day

(Source: UN Habitat, 2015).

A phenomenon exclusive to the rail and subway transportation sector was encountered in the process of data gathering for this LCA, and that is the existence of Product Category Rules (PCRs) and Environmental Product Declarations. These related concepts are covered by ISO 14025, which provides rules for their elaboration as well. PCRs are specific guidelines to calculate the environmental impact of products within the same product category. A product category is defined as a group of products with similar characteristics. Since PCRs require a Program Operator, which can be a group of companies, an industrial sector, trade organization or a public authority, the European rail manufacturers have found it to their benefit to come together and start publishing PCRs and EPDs. These EPDs follow the Product Category Rules for Rail Vehicles (PCR 20009:05).

The purpose of a PCR is to leave less room for interpretation, by specifying, the functional unit that should be used, or specific databases, or impact assessment methods or categories that should be used in an LCA. By meeting a PCR's requirement, a company or corporate entity can present an EPD, which is a concise document that contains the relevant environmental information about a product. Bombardier (2012), Alstom (2006), and Siemens (2014) are some of the examples of the EPDs referenced in this study.

Table 3-26 shows some salient characteristics of metros worldwide, obtained mostly from EPDs.

Table 3-26. Dimensions, Passenger Capacities and Operating Speeds for Selected Metros Worldwide.

Vehicle (source)	Location	# of cars	Length (m)	Width (m)	Total passengers	Seated passengers	Standees (/m2)	Operating speed (km/hr)
Bombardier Azur (a)	Montreal, Canada	9	152.4	2.5	1,539	272	4	72.4
Ansaldo Breda Metro (b)	Rome, Italy	6	109.8	2.9	1,204	194	6	90
Siemens Inspiro (c)	n/a	6	117.8	2.8	1,450	256	7	80
CAF Metro units M300 (d)	Helsinki, Finland	4	88.2	1.4	1,028	238	n/a	90
Toronto Rocket (e, f)	Toronto, Canada	6	137.8	3.1	1,100	384	6	88

Sources: (a) Bombardier-Alstom 2015; (b) Del Pero *et al*. 2015; (c) Siemens 2014b; (d) CAF 2015b; (e) Bombardier 2016b; (f) TTC 2011

In order to obtain an estimate of the energy consumption for different metro systems around the world, Table 3-27 presents a summary of this information.

Table 3-27. Energy consumption for Selected Metros around the World.

Location	Energy Consumption	Units	Energy Use (MJ/Km)	Source
Montreal, Canada	26.0	kWh/km	93.6	Bombardier-Alstom 2015
Rome, Italy	16.7	kWh/km	60.1	Del Pero et al. 2015
Not yet deployed	9.6	Wh/pkm	50.2	Siemens 2014b
Helsinki, Finland	11.8	kWh/km	42.6	CAF 2015b

STC-Metro, the transit authority in charge of the Mexico City subway, reports that the energy consumed by the train was an average of 18.75 kWh/VKT, during the years of 2014 and 2015, and of 19.30 kWh/VKT during 2016 (STC, 2016b). Consequently, the latter number, being higher, was the one chosen to edit Simapro's record for train operation, since it was deemed a more conservative estimation of electricity usage.

Construction Methods for the Subway

Most frequently, subway stations that were built by different constructions techniques are part of the same subway line. For classification purposes, depending on the construction method used, stations are classified as (Covitur, 1987; MTA, 2003):

1. Deep tunnel station. The depth of the track beneath the subgrade level is approximately 8.5 meters, or more. This type of tunnel may be a double track tunnel section or an independent tunnel section for each track.

2. Subterranean, with a box section. The term "box" refers to a concrete box. These stations can be further classified as:

a) Rectangular box with “Milan” structural walls. These are slurry walls, placed in trenches, regularly with a clamshell excavator. The "Milano method" was named after the building technique employed in the building of Milan's subway, in 1957.

b) Rectangular box with accompanying sheet piles (poling boards)

c) Conventional box

3. Superficial station. These stations can be:

a) Ground-level box, composed of concrete floor, low walls and steel mesh

b) Superficial, directly placed on top of the natural terrain

4. Elevated or Aerial station. They are built on a viaduct formed by locks and low walls, supported by pillar columns.

Irrespective of the station construction, the tunnels required for an underground subway are, undoubtedly, the most demanding task of a subway system construction. These tunnels, along with the stations, are generally built using a combination of three main tunneling techniques:

a) Mechanized boring machines or tunnel boring machines, “TBMs”
b) Conventional mining techniques, including “drill and blast” construction and road headers
c) Cut-and-cover construction

Tunnel boring machines (TBMs) are used as an alternative to drilling and blasting (D&B) methods in rock and conventional mining methods. TBMs are preferred over other methods, and are currently considered the “modern” method of tunnel excavation, because they limit the disturbance to the surrounding ground and produce a smooth tunnel wall, which significantly reduces the cost of lining the tunnel. These advantages make TBMs suitable for use in heavily urbanized areas. In fact, they are the main reasons why it is reasonable to assume that in the future, construction for new subway lines in already heavily urbanized metropolitan areas will be done primarily through the use of TBMs for tunnel and other underground infrastructure construction. The principal drawback of TBMs is their upfront cost, and they can also be difficult to transport. However, as modern tunnels become longer, the cost of tunnel boring machines versus drill and blast methods will continue to decrease, mainly due to the fact that tunneling with TBMs is much more efficient and results in shortened completion times.

A TBM’s advance rate depends on the type of machine used, which is largely determined by the soils on which it will be boring. Although a Robbins Crossover (XRE) TBM excavating for Mexico City’s main wastewater infrastructure program, the “Túnel Emisor Oriente,” or Eastern Discharge Tunnel, (CONAGUA, 2008), achieved two national records for TBM advance in June 2016—one for excavating 57 m in one day and another for boring 702.2 m in one month—the engineers in charge of the most recent subway construction experience with TBMs in Mexico City, that of Line 12, estimated the advance of its corresponding TBM, an Earth Pressure Balance machine, in approximately 10 meters/day (Robbins, 2018).

Additionally, it is reported that as the EPM TBM for Line 12 advanced, it lined the tunnel with 40-cm thick universal concrete segments. (*ibidem*).

Since both mechanized and traditional tunneling do in fact have their origin in mining operations, they are commonly referred to as “mining” techniques. The greatest advantage to the public and inhabitants of the areas adjacent to where the new subway lines will be built is that these construction methods allow for tunnel and station excavation to occur below the street surface without any substantial disruption above. Generally, the only visible evidence to the public of a mining operation, or in fact, of any construction occurring, is the presence of vertical shafts that connect the ground surface to the tunnel below. It is through these vertical shafts that the TBMs and/or other heavy machinery for mining are lowered into the tunnel, and eventually extracted from it once the work has concluded. An additional function of these shafts is to remove the excavated rock and soils, together called “spoils”.

Nowadays and in a seemingly worldwide trend, mining techniques are much preferred over cut-and-cover construction because they cause fewer environmental and community disruptions. In the case of Mexico City, although the first three lines of the Metro-subway were built with a combination of cut-and-cover techniques and slurry walls, in the present day such a scenario appears extremely unlikely. Both the urban density and the traffic demands of highly transited corridors -the ones on which a subway line would be most beneficial—make it unfeasible to envision that circulation could be diverted for the amount of time needed to build a superficial metro, or an underground one, using these cut-and-cover techniques.

A further argument on why it is unlikely to anticipate that future construction for subway lines in Mexico City will occur in the form of superficial stations or elevated viaducts, (instead of underground stations) is provided by earthquake engineering. A seismic-risk assessment study for all lines and facilities of the STC-Metro system was conducted in 2017 (IIUNAM, 2017) by research teams of the Institute of Engineering of the National Autonomous University of Mexico. A large-scale earthquake, (magnitude > 8; with its epicenter in the coasts of the Pacific-bordering state of Oaxaca), and its attendant expected damages, were modeled in this study. Results displayed a relatively low seismic risk for all lines of the Metro system, except for the superficial lines “A” and “2.” Since these lines were built on soils that are part of the ancient lakebed of Mexico City, and hence experience high accelerations and seismic intensities during earthquake events, the damages forecasted for these two lines was greater than that expected for subterranean lines. The latter, which account for 61% of the Metro's network, experienced lower seismic intensities and consequently, much lower expected damages.

Table 3-28 presents the parameters that were declared in Simapro for the subway system.

Table 3-28. Simapro input and calculated parameters for the Subway system.

Input parameters	
TrainLifetime	33
TrainLifetime45	45
RailLifetime	33
DepotLifetime	60
StationLifetime	60
VKTDaily	387
DaysOperationPerYear	300
RailKm	23.609
VKTRailway	185005375.8
VKTRailway45	252280058
NumberofTrains	51
NumberofStations	19
NumberofDepots	2
Ridership1530	1530
Ridership2295	2295
Ridership918	918
Calculated parameters	
VKTAnnual	VKTDaily*DaysOperationPerYear
VKTLifetime	VKTAnnual*TrainLifetime
VKTLifetime45	VKTAnnual*TrainLifetime45
Rail_TrainLifetime	TrainLifetime/RailLifetime
Rail_TrainLifetime45	TrainLifetime45/RailLifetime
Station_TrainLifetime	TrainLifetime/StationLifetime
Station_TrainLifetime45	TrainLifetime45/StationLifetime
Depot_TrainLifetime	TrainLifetime/DepotLifetime
Depot_TrainLifetime45	TrainLifetime45/DepotLifetime
PKTLifetime	VKTLifetime*Ridership1530

To estimate the hours of operation for the construction of the tunnels, the following geometrical formula was used:

$$V = Pi * r^2 * h \qquad \text{Equation 3 – 2}$$

where r is the radius of the excavation tunnel and

h is the longitudinal distance of the tunnel.

Figure 3-25 depicts the rails (both guide curve and security rails), concrete sleepers and ballast considered for a prototypical ballasted subway track.

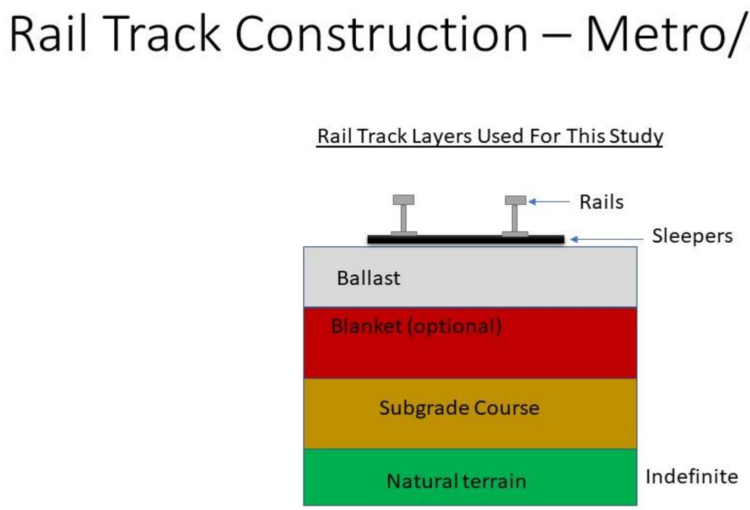


Figure 3-25. Railway Design for Train, Subway.

With the above information, the materials and processes for a unit kilometer of double track for the subway were calculated. The list of these that was inputted into Simapro is shown in Table 3-29.

Table 3-29. Input Materials and Processes for Road Construction, Subway.

Materials/assemblies	Amount	Unit	Comment
Gravel, round {GLO}| market for | Alloc Rec, U	562938.66	ton	Ballast
Water, decarbonized, at user {GLO}| market for | Alloc Rec, U	2550.48	ton	
Cement, Portland {RoW}| market for | Alloc Rec, U	4959.27	ton	
Sand {GLO}| market for | Alloc Rec, U	13211.49	ton	
Gravel, crushed {GLO}| market for | Alloc Rec, U	22065.55	ton	For Cement
Steel, low-alloyed {GLO}| market for | Alloc Rec, U	105.98	ton	Guide Curve
Steel, unalloyed {GLO}| market for | Alloc Rec, U	104.38	ton	Security rail
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, U	179.26	ton	Tracks
Processes			
Excavator, technology mix, 500 kW, Mining GLO	1715000	kg	

Table 3-30 lists the train manufacturing record, noting that it was edited both in a weight basis, and also in substituting the Swiss electricity mix with the average European one. This is due to the fact that it is known that Mexican subway trains are manufactured within the confines of the European Union; mostly in France and Spain, but not exclusively.

Table 3-30. Train Manufacturing, Subway.

Processes			
Train, passenger, regional {CH}| production edited for RER Electricity mix | Alloc Rec, U	1.292	p	Based on weight, 221 t versus 171 tons - 1.292 factor. Substituted for RER electricity mix as well.

Table 3-31 shows the train operation record after it was edited to substitute Mexican electricity. As part of this product stage, the maintenance for the train is also included.

Table 3-31. Train Operation, Subway.

Materials/assemblies	Amount	Unit
Train Manufacturing	(1/VKTLifetime) /Ridership	p
Processes		
Transport, passenger train {CH}| regional edited for Mexican electricity | Alloc Rec, U	1	personkm
Maintenance, train, passenger, regional {CH}| processing | Alloc Rec, U	(1/VKTLifetime) /Ridership	p

3.4.3 Impact Assessment

After an initial screening and selection of Environmental Impact Assessment methods, the BEES method was selected for this portion of the LCA study. Results are listed in Chapter 4, Section 4.4.2.

3.4.4 Interpretation

3.4.4.1 Limitations of Simapro

The main limitation of the software relative to this LCA was again the lack of specific records for detailed pieces of machinery. Although the hours of operation had been individually calculated, these hours were lumped into a general category. It is considered that while regrettably a certain degree of precision was lost by this lumping together of data, nevertheless this did not have a significant negative effect in the overall data quality, nor eventually on the results of this study.

3.4.4.2 Other Assumptions

For the Subway system, it was decided that for l all the modules of the infrastructure subsystem (station, depot and railway), a 3000 PSI concrete with its attendant materials (cement, water, sand and gravel) would be used.

3.5 Methodology for Research Objective 3 (Cumulative Exergy Method and ExLCA)

3.5.1 Cumulative Exergy Demand (CExD) Method

To accomplish Objective 3, Simapro's method to calculate the Cumulative Exergy Demand was employed. As mentioned previously, Cumulative Exergy Demand (CExD) is used to quantify the life cycle exergy demand of a product, and is defined as the sum of exergy of all resources required to provide a process or product.

Exergy, as well as energy content, are expressed in MJ. Exergy, an expression of the quality of energy, is a measure of the useful "work" that can be extracted from an energy carrier. In this method exergy is used as a measure of the potential loss of "useful" energy resources.

One of the major advantages of this method as contained in Simapro, is that the exergy concept was applied to the resources of the Ecoinvent database, so it has been taken directly from Ecoinvent 2.0. The amount of substances present is compatible with the EI 2.0 database and extended for other databases. An additional advantage of this method in Simapro is that it considers chemical, kinetic, hydro-potential, nuclear, solar-radiative and thermal exergies, as defined in Bösch, 2007.

For characterization purposes, although the impact category indicator is usually grouped into eight resource categories, Simapro presents ten impact categories: non-renewable fossil; non-renewable nuclear; renewable, kinetic; renewable, solar; renewable, potential; non-renewable, primary; renewable, biomass; renewable, water; non-renewable, metals; non-renewable, minerals.

In this method, exergy characterization factors for 112 different resources were included in the calculations.

$$CExD = \sum_{i} m_i * Ex_{(ch),i} + \sum_{j} n_j * r_{ex-e(k,p.n.r,t),j}$$

$CExD$ = cumulative exergy demand per unit of product or process (MJ-eq)

m_i = mass of material resource (kg)

$Ex_{(ch),i}$ = exergy per kg of substance i (MJ-eq/kg)

n_j = amount of energy ratio of energy carrier j (MJ)

ch = chemical

k = kinetic

p = potential

n = nuclear

r = radiative

t = thermal energy

The type of exergy assigned to each resource by Simapro follows the below guidelines:

- Chemical exergy is applied on all material resources (that are not reference species in the reference state), for biomass, water and fossil fuels
- Thermal exergy is applied for geothermic uses, where heat is withdrawn without matter extraction
- Kinetic exergy is applied on the kinetic energy in wind used to drive a wind generator
- Potential exergy is applied on potential energy in water used to run a hydroelectric plant
- Nuclear energy is applied on nuclear fuel consumed in fission reactions
- Radiative exergy is applied on solar radiation impinging upon solar panels

Regarding normalization and weighting, normalization is not part of this method, and as far as weighting is concerned, in order to get a total (“cumulative”) exergy demand, each impact category is given the weighting factor 1.

3.5.1 ExLCA for Research Objective 3, Part 1 (BRT)

To achieve Objective 3, conducting an Exergetic Life-Cycle Assessment for the BRT System, the Cumulative Exergy Demand (CExD) method of Impact Assessment available within Simapro was used. To provide a point of reference and comparison, it was decided to also run the Cumulative Energy Demand (CED) method.

Results of these simulations are presented in Chapter 4, Section 4.5.1.

3.5.2 ExLCA for Research Objective 3, Part 2 (Private Car)

To achieve Objective 3, conducting an Exergetic Life-Cycle Assessment for the Private Car System, the Cumulative Exergy Demand (CExD) method of Impact Assessment available within Simapro was used. To provide a point of reference and comparison, it was decided to also run the Cumulative Energy Demand (CED) method.

Results of these simulations are presented in Chapter 4, Section 4.5.2.

3.5.3 ExLCA for Research Objective 3, Part 3 (Subway)

To achieve Objective 3, conducting an Exergetic Life-Cycle Assessment for the Subway System, the Cumulative Exergy Demand (CExD) method of Impact Assessment available within Simapro was used. To provide a point of reference and comparison, it was decided to also run the Cumulative Energy Demand (CED) method.

Results of these simulations are presented in Chapter 4, Section 4.5.3.

3.6 Methodology for Research Objective 4 (Conduct Sensitivity Analysis to determine Range of Environmental Impacts)

To accomplish Objective 4, a sensitivity analysis was conducted. When an evaluation of the influence that the major assumptions have on the results is needed, a sensitivity analysis is performed. This is done by simply changing the assumption (one each time, and not more than one simultaneously) and recalculating the LCA. Consequently, a better sense on how different assumptions affect the results is obtained. Sensitivity analysis typically shows LCA results as heavily dependent on some of the assumptions. During the course of performing an LCA, the practitioner develops an intuition or idea of which may be these variables, and may propose these as the first to be tested in the sensitivity analysis. As almost all parts of an LCA, sensitivity may also be an iterative process, with further refinement of the variables, in this context known as "sensitivity parameters," possible as the LCA progresses and eventually concludes.

3.6.1 Sensitivity Parameters

3.6.1.1 Sensitivity Parameters for BRT

After running the initial screening Environmental Impact Assessment for the selection of Impact Assessment method, and the base case scenario for the BRT system, which provided a good understanding of its behavior, the variables chosen for sensitivity analysis were:

A) Ridership, sometimes known as occupancy, in units of passengers. A distinction was made between peak and off-peak ridership.

B) Vehicle's Lifetime. Since the average distance traveled, in VKT, both annually and in a lifetime basis is a dependent variable on the vehicle's lifetime, by altering the latter, the effect of different VKTs was also measured.

C) Infrastructure's Lifetime. The lifetime of the most significant modules within the infrastructure subsystem, the stations, was altered to gauge the effects of this parameter upon the system.

The results of this sensitivity analysis are shown on Chapter 4, Section 4.6.1.

3.6.1.2 Sensitivity Parameters for Private Car

After running the initial screening Environmental Impact Assessment for the selection of Impact Assessment method, and the base case scenario for the Private Car system, the variables chosen for sensitivity analysis were:

A) Ridership, sometimes known as occupancy, in units of passengers. Scenarios were run for low, average and high (or maximum) occupancy in the car.

B) Vehicle's Lifetime. Since the average distance traveled, annually and during the vehicle's lifetime, measured in VKT, is a dependent variable on the vehicle's lifetime, by altering the latter, the effect of different VKTs was also measured.

C) Infrastructure's Lifetime. The only module within the infrastructure subsystem in this case, the flexible pavement for the roadway, was modeled with different lifetimes to understand the effects of this parameter upon the system.

The results of this sensitivity analysis are shown on Chapter 4, Section 4.6.2.

3.6.1.3 Sensitivity Parameters for Subway

After running the initial screening Environmental Impact Assessment for the selection of Impact Assessment method, and the base case scenario for the Subway system, the variables chosen for sensitivity analysis were:

A) Ridership, or occupancy, in units of passengers. Scenarios were declared for peak and off-peak ridership values.

B) Vehicle's Lifetime. Since the average distance traveled, annually and during the vehicle's lifetime, measured in VKT, is a dependent variable on the vehicle's lifetime, by altering the latter, the effect of different VKTs was also measured.

C) Electricity mix. The Mexican electricity mix that was used for the base case scenario was substituted for the average American electricity mix, to understand the effects of this parameter upon the system.

The results of this sensitivity analysis are shown on Chapter 4, Section 4.6.3

Chapter 4

RESULTS AND ANALYSIS

4.1 Results for Objective 1 (Development of TransportLifeCAMM)

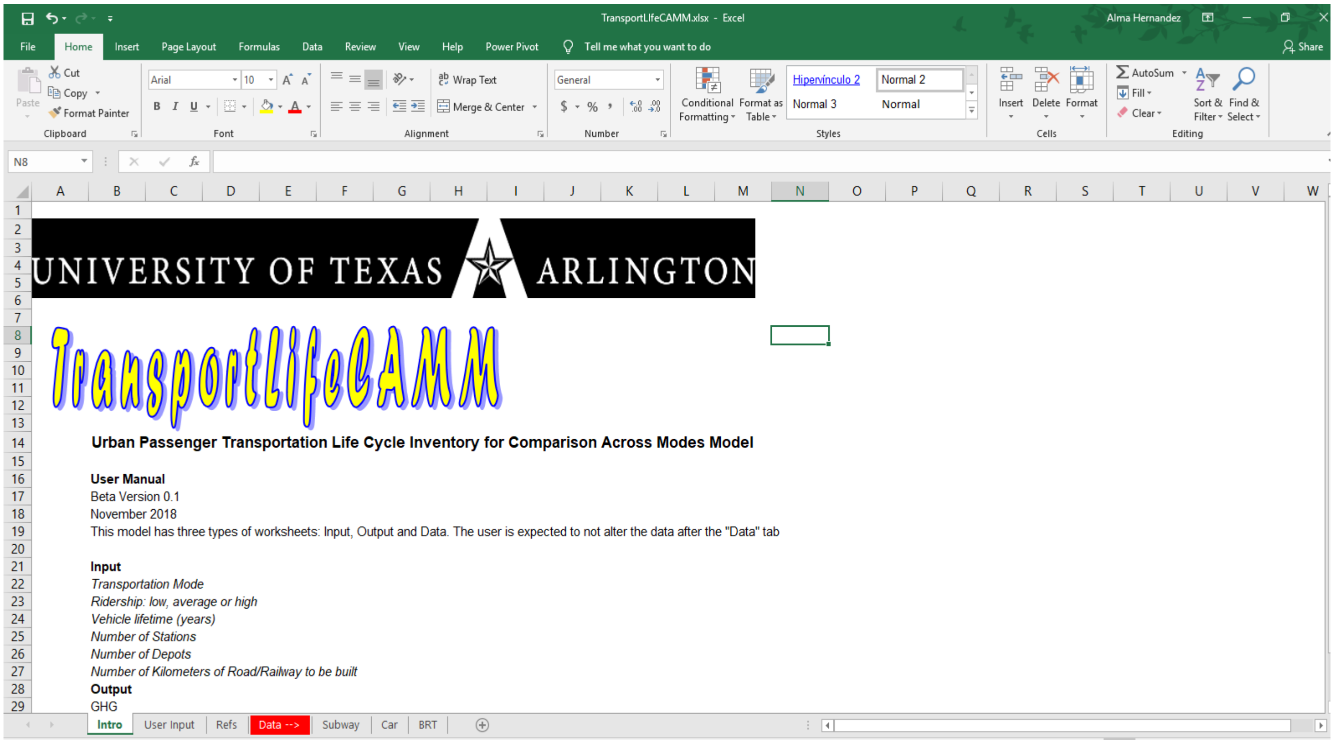
As mentioned in Section 3.1.2.1, an initial screening of Environmental Impact Assessment (EIA) methods was carried out in order to select the method(s) that would best accomplish the purposes of this work. Table 4-1 summarizes the information sources for every life cycle phase for each of the modes studied in this dissertation. In general terms, the raw materials extraction phase was called upon by the manufacturing record, for each one of the vehicles, and was used as required, according to engineering calculations, for the construction of each of the corresponding infrastructure modules for each mode (road or railway, station and depot for bus and subway; road and vehicle for the car). For all three vehicles, the Simapro record that more closely resembled the vehicle under study was edited, with the best information available, to match as faithfully as possible the actual conditions on the ground for each system. The operation phase of the onroad vehicles, as well as their corresponding energy (fuel) subsystem, were covered with modified USLCI records, that take advantage of information both from GREET and MOVES. End-of-life for the vehicles was considered only as it is already included in the manufacturing records, respectively, for each vehicle.

Table 4-1. Data Sources per Life Cycle Phase and Mode for Bus, Car and Subway.

	Raw Materials/Manufacturing	Maintenance	Operation	End-of-Life
Bus Vehicle	Modified Simapro record for Volvo 8500	Modified Simapro record for Bus Maintenance	Modified USLCI record, based on MOVES. Scaled up by weight, and with modified ridership	As considered in Simapro record for Volvo 8500
Bus Fuel	USLCI record, based on GREET	USLCI record, based on GREET	Modified USLCI record, based on MOVES. Scaled up by weight, and with modified ridership	Not applicable – combustion of fuel results in emissions
Bus Stations	Own calculations, based on architectural drawings	Own calculations, based on transit authority's reports	Own calculations, based on transit authority's reports	Information not available
Bus Depots	Own calculations, based on architectural drawings	Own calculations, based on transit authority's reports	Own calculations, based on transit authority's reports	Information not available
Bus Roadway	Own calculations, based on own concrete design and public information requests	Own calculations, based on Mexico City's government and Public Work Secretariat's reports	Own calculations, based on Mexico City's government and Public Work Secretariat's reports	Information on recycling of hydraulic concrete not available
Car Vehicle	Modified Simapro record for Volkswagen Golf A4, scaled up by weight	NISSAN Versa's user manual and technical specifications	Modified USLCI record, based on MOVES. Scaled up by weight, and with modified ridership	As considered in Simapro record for Volkswagen Golf A4
Car Fuel	As considered in USLCI record, based on GREET	As considered in USLCI record, based on GREET	Modified USLCI record, based on MOVES. Scaled up by weight, and with modified ridership	Not applicable – combustion of fuel results in emissions
Car Roadway	Own calculations, based on own concrete design	Own calculations, based on own concrete design and reports	Own calculations, based on own concrete design and Mexico City's government reports	Information on recycling of asphalt not available
Subway Vehicle	Modified Simapro record for Zurich S-subway train	- Modified Simapro record for Zurich S-subway train -	- Technical Manuals from STC-Metro (Transit authority) - Published electrical usage in kWh/km, from STC-Metro - Environmental Product Declarations (EPD).	Transit authority claims no trains have been scrapped yet
Subway Fuel	Mexican electricity mix	Mexican electricity mix	- Published electrical usage in kWh/km, from STC-Metro - Published emission factors for Mexican electricity mix	Not applicable – off-site combustion of fuel to generate electricity results in emissions
Subway Stations	Own calculations, based on STC-Metro reports	Own calculations, based on transit authority's reports	Own calculations, based on transit authority's reports, theses and technical manuals	Information not available
Subway Depots	Own calculations, based on STC-Metro reports	Own calculations, based on STC-Metro reports	Own calculations, based on STC-Metro reports	Information not available
Subway Railway	Own calculations, based on STC-Metro reports	Own calculations, based on STC-Metro reports	Own calculations, based on STC-Metro reports, theses, and technical manuals	Concrete sleepers replaced previous wooden sleepers, after 35 years of use

4.1.1 User Inputs in TransportLifeCAMM

Figure 4-1 presents a screenshot of the spreadsheet-based TransportLifeCAMM model's introductory page. A brief user manual provides a basic orientation, and explains that the model contains three types of worksheets: Input, Output and Data worksheets. The user is not meant to alter, delete, or edit in any way the data that is found after the "Data" tab. The data contained in the tabs (worksheets) after the "Data" tab was obtained by the simulation runs for the base case, as well as for the sensitivity analysis runs, for each of the modes. These runs are detailed in subsequent sections in this Chapter.



Urban Passenger Transportation Life Cycle Inventory for Comparison Across Modes Model

User Manual
Beta Version 0.1
November 2018
This model has three types of worksheets: Input, Output and Data. The user is expected to not alter the data after the "Data" tab

Input
Transportation Mode
Ridership: low, average or high
Vehicle lifetime (years)
Number of Stations
Number of Depots
Number of Kilometers of Road/Railway to be built
Output
GHG

Figure 4-1. Screenshot of TransportLifeCAMM – Introductory Page

For clarity of usage, Table 4-2 lists the user inputs for each one of the transportation modes. It must be pointed out that the first choice that the user must make is that of the mode: bus, car or subway. Following that, the user can choose between low, average and high ridership; the average or expected lifetime of the vehicle (in years), and how many of each infrastructure module exists — or will exist— in their particular system.

Table 4-2. User Inputs for TransportLifeCAMM per Transportation Mode.

First choice: Transportation Mode.		
Bus	Car	Subway
Ridership: Low (90 passengers), Average (160 passengers), High (240 passengers)	Ridership: Low (1 passenger), Average (1.7 passengers), High (5 passengers).	Ridership: Low (918 passengers), Average (1530 passengers), High (2295 passengers).
Vehicle lifetime (years)	Vehicle lifetime (years)	Vehicle lifetime (years)
Number of road kilometers built (hydraulic concrete)	Number of road kilometers built (asphaltic concrete)	Number of railway kilometers built (triple tracks: guide curve, wearing track, safety rail)
Number of Stations		Number of Stations
Number of Depots		Number of Depots

Underlying the calculations for the systems on which TransportLifeCAMM is based, there is a set of assumptions that cannot be readily changed by the user. While great care was taken in making these assumptions as generic as possible, to ensure that TransportLifeCAMM could be applied to as many local circumstances as possible, it is important to keep these assumptions in mind. Table 4-3 lists the assumptions, per mode, that the user cannot change in the model. Some of these assumptions were made in the development of the TransportLifeCAMM model, while others are derived from system boundary definitions made by others, specially by several data sources. Among these, the fact that the user cannot change the fuel economy for the onroad vehicles is a direct result of the assumptions made by the USLCI records, which take 1,000 liters of fuel (ultralow sulfur diesel and gasoline, respectively, for the bus and the car) as the reference flow, thereby fixing a fuel economy by tying the amount of fuel to the lower heating value of that fuel. As with many other assumptions made throughout, this value provides the best representative value for the average, most frequent case, but unfortunately diminishes the options available for the end user, ultimately.

Table 4-3. Assumptions User Cannot Change in TransportLifeCAMM.

Bus	Car	Subway
Fuel economy	Fuel economy	Ridership: Low, Average, High
Make and model of the bus	Make and model of the car	Number of cars per train
Number of pavement layers used in the hydraulic concrete, and their chemical composition.	Number of pavement layers used in the asphaltic concrete, and their chemical composition.	Assumption of triple tracks and double railway (two directions) per unit kilometer
Dimensions of Stations (fixed by model as per APTA's standards).		Dimensions of Stations
Dimensions of Depots (fixed by model as per APTA's standards).		Dimensions of Depots

It is hoped that further work on TransportLifeCAMM will provide the user with the opportunity to model the stations and depots, not only based on their number, but also based on their length, from which the other dimensions and construction materials' volumes will be calculated and simulated.

Additionally, although the flexible, asphaltic pavement was initially associated with the car system, and the hydraulic concrete with the bus, a future version of TransportLifeCAMM will allow the user to choose either concrete irrespective of the car or bus system.

4.1.2 Generic Infrastructure Modules for Bus and Subway

Although the construction materials and processes for the building of the roadway, stations and depots for the bus was initially based almost exclusively on available architectural drawings, all engineering calculations were ultimately edited to meet the APTA's standards for stations, stops and transit running ways (APTA BTS-BRT-RP-002-10 and APTA BTS-BRT-RP-003-10, October, 2010). Consequently, their design is applicable to any BRT system in North America.

Similarly, the building of the infrastructure modules for the subway was made as generic as possible in order to adequately represent the conditions in any city in the United States and Mexico.

While the initial measurements, dimensions and construction volumes were taken from Mexico City's past and current technical manuals, information from other metro/subway systems around the world and in North America was also reviewed. Among these, information for the New York, Boston and Sydney subways was consulted, and thus, the information ultimately used to design the case study was extrapolated were necessary, to cover the majority of similar cases. For instance, while the very first technical manuals of the Mexico City subway recommended a 50-centimeter depth of ballast to accompany the rails, more modern usage (Line 12 in Mexico City, the most recent in the STC-Metro as of this writing) called for a depth of 30 centimeters. Similarly, the subways of Germany, Zurich, New York, and Boston (Schmied and Mottschall, 2010; Tuschmid, 2011; New York City Transit Authority, 2018; Massachusetts Bay Transportation Authority, 2018) report a depth of 30 centimeters of ballast as common usage. Although the Sydney, Australia subway runs on ballast-less tracks, consisting of concrete sleepers and rails only, it was considered that a generic railway for North America would be well represented with a standard-gauge track -which is the most common gauge in the United States and Mexico; Canada uses the wide gauge—running on 30 centimeters of ballast.

Therefore, the assumptions made for all infrastructure modules of the bus and subway systems ensure that their simulations and results are applicable to any city in North America.

4.1.3 Initial Screening for BRT

Once the BRT system was built, with its energy, vehicle and infrastructure subsystems, initial screenings were run. Figure 4-2 presents results at the characterization phase, and Table 4-4 shows these same initial screening inventory results for some criteria air pollutants (CAP), with both the total amount and the subtotals for each infrastructure module's life cycle, respectively. Additionally, Table 4-4 shows the percentage of each pollutant for the vehicle (bus) subsystem's life cycle and for the station module's life cycle. It is pointed out that these percentages represent inventory values, before they are assigned to different impact categories depending on the different considerations of each impact assessment method. It can be seen from this table that the vehicle (BRT bus) generates the vast majority of air pollutants, and in some cases almost the totality of them, as is true with the nitrogen oxides, which are generated in 97% by the bus. This is in line with the known chemistry for the generation of nitrogen oxides, which result primarily from the combustion of fossil fuels; as such, it is an expected result. In other impacts reflected in this initial screening, about a third of the land occupation impact corresponds to the station, which stands to reason.

For the BRT System, the Base Case was defined as an Articulated Bus, with a lifetime of 12 years, a ridership of 160 passengers, a road lifetime of 20 years, for the hydraulic concrete in this instance, and a lifetime of 25 years both for the stations and the depots.

Figure 4-3 to Figure 4-6 show the characterization, normalization, damage assessment and single score phases of the Impact 2002+ method when applied to the base case of the BRT. From these figures it is clear that the vehicle subsystem is the one with the greatest impacts. It can also be seen that the impact categories with the largest impact are human health, followed by climate change, resources, and in a distant fourth place, by ecosystem quality. Figure 4-7 shows the network diagram for the single score phase of the Impact 2002+ method, also for the BRT's base case. In this latter figure, and in Table 4-5**Error! Reference source not found.**, it can be observed that the vehicle's percentage contribution in each impact category, relative to the system, varies from 77% to 90%; 85.5 %, on average, according to the Impact 2002+ method. This is in line with initial expectations, as other authors (Chester, 2009) have reported that the infrastructure subsystem, or "component" generally accounts for close to 15% of the emission inventory.

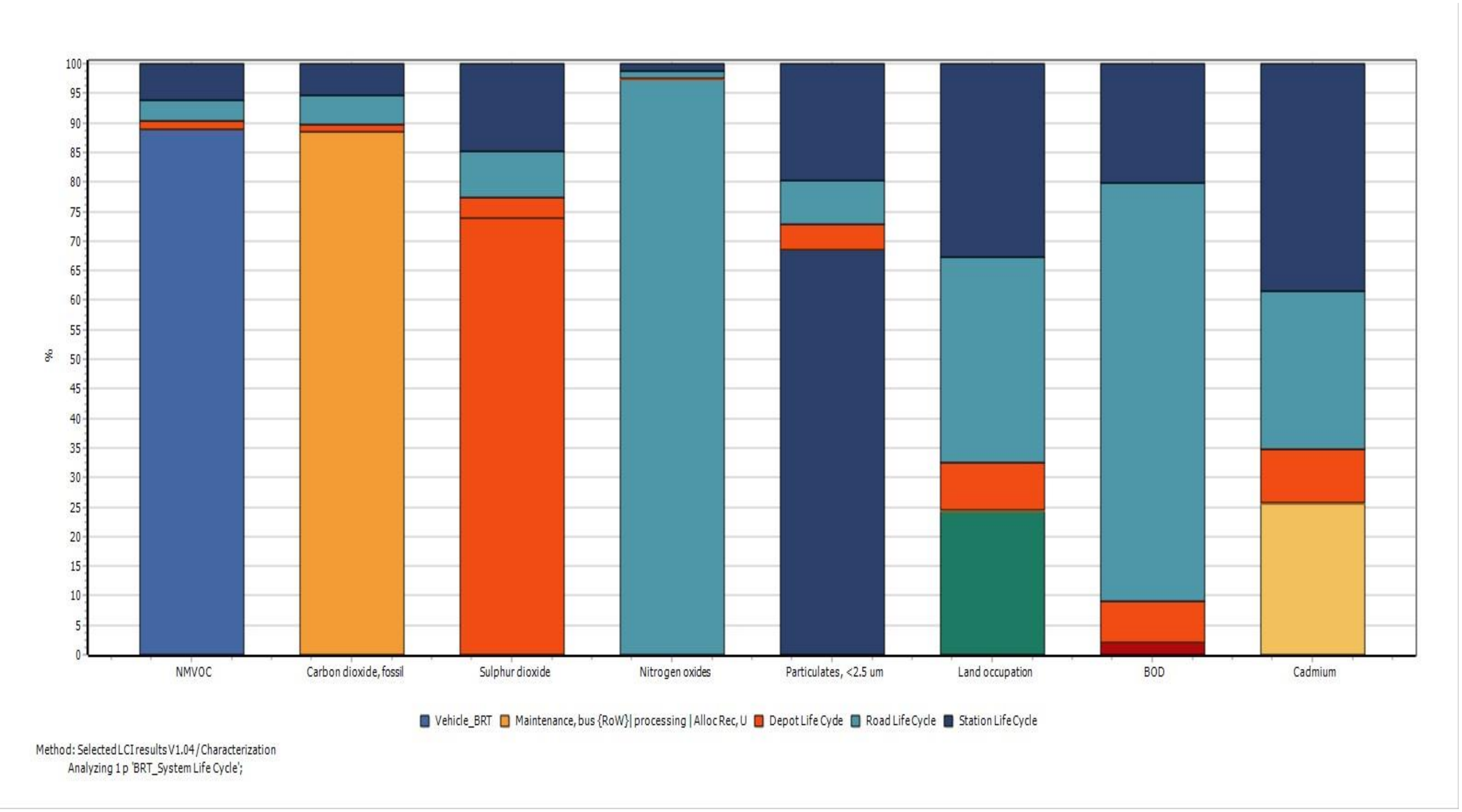


Figure 4-2. BRT, Base Case, Characterization, Selected LCI Results (Simapro software)

Table 4-4. Selected LCI Results for BRT.

Impact category	Unit	Total	Vehicle BRT	Maintenance, bus {RoW}| processing | Alloc Rec, U	Depot Life Cycle	Road Life Cycle	Station Life Cycle	Vehicle (Bus) Percentage	Station Percentage
NMVOC	kg	7.91E-06	7.03E-06	5.83E-10	1.11E-07	2.73E-07	4.91E-07	88.93 %	6.21 %
Carbon dioxide, fossil	kg	0.0155	0.013692	1.54E-06	0.000216	0.00074	0.000839	88.40 %	5.42 %
Sulphur dioxide	kg	1.96E-05	1.45E-05	5.95E-09	6.7E-07	1.57E-06	2.89E-06	73.82 %	14.72 %
Nitrogen oxides	kg	0.000149	0.000145	3.33E-09	4.84E-07	1.79E-06	1.85E-06	97.23 %	1.24 %
Particulates, <2.5 µm	kg	6.86E-06	4.7E-06	2.72E-09	2.93E-07	5.11E-07	1.35E-06	68.54 %	19.70 %
Land occupation[a]	m^2a	0.000114	2.79E-05	7.82E-08	9.31E-06	3.98E-05	3.74E-05	24.38 %	32.65 %
BOD	kg	0.000135	2.82E-06	8.72E-10	9.4E-06	9.58E-05	2.74E-05	2.08 %	20.23 %
Cadmium	kg	1.51E-12	3.85E-13	1.26E-15	1.37E-13	4.03E-13	5.8E-13	25.54 %	38.51%

[a] Land occupation is measured in units of m^2a, or square meters per year: the surface that changes its land use during that period.

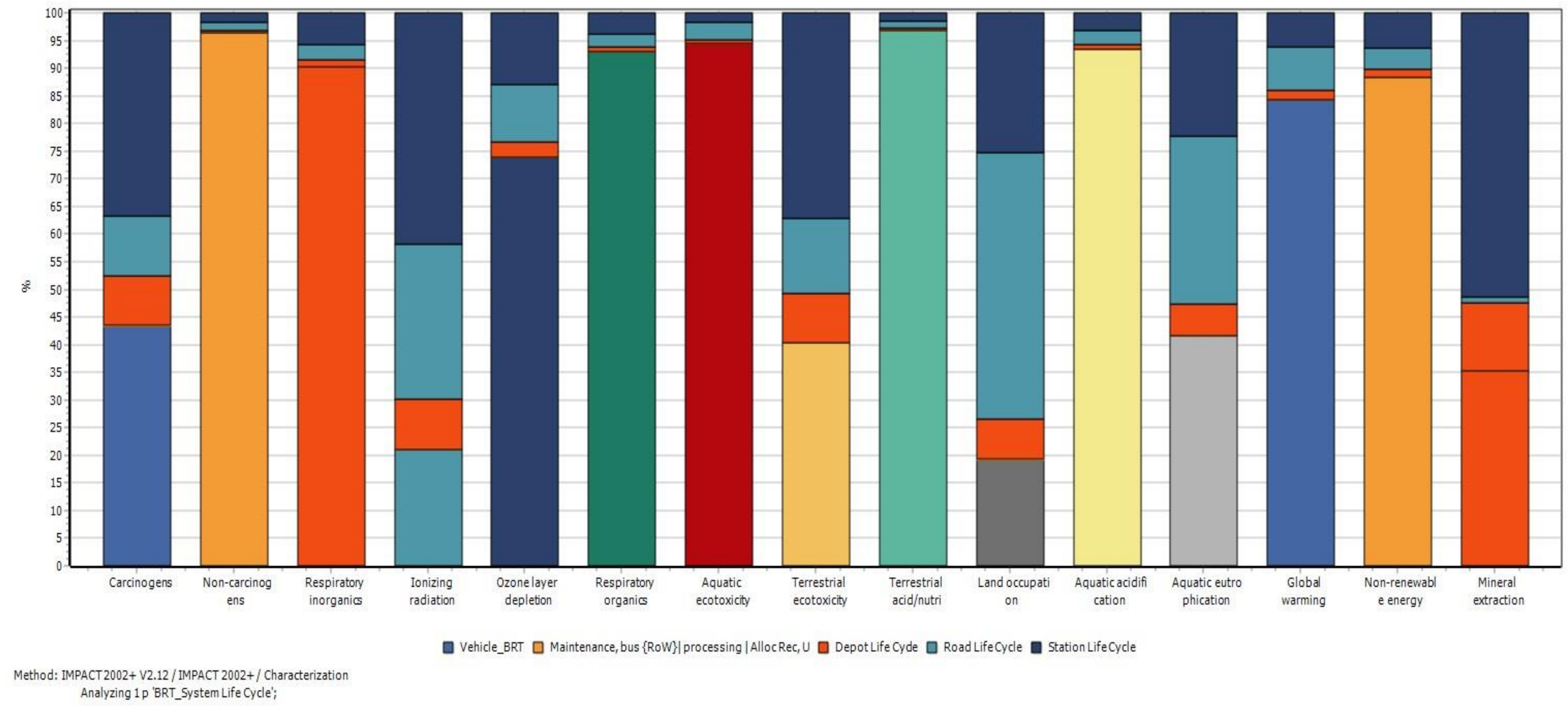


Figure 4-3. BRT Base Case, Characterization, Impact 2002+ (Simapro software)

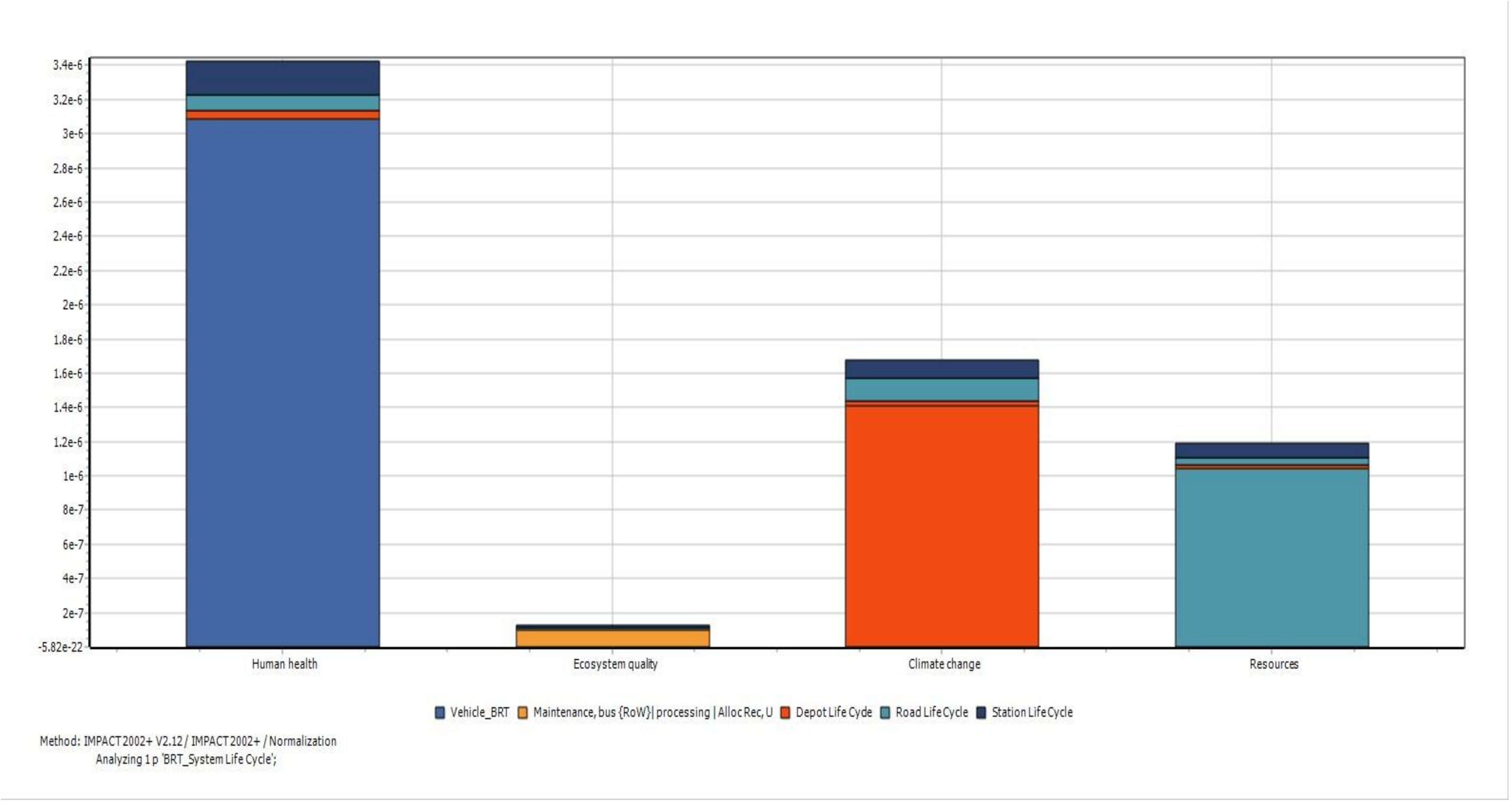


Figure 4-4. BRT, Base Case, Normalization, Impact 2002+ (Simapro software).

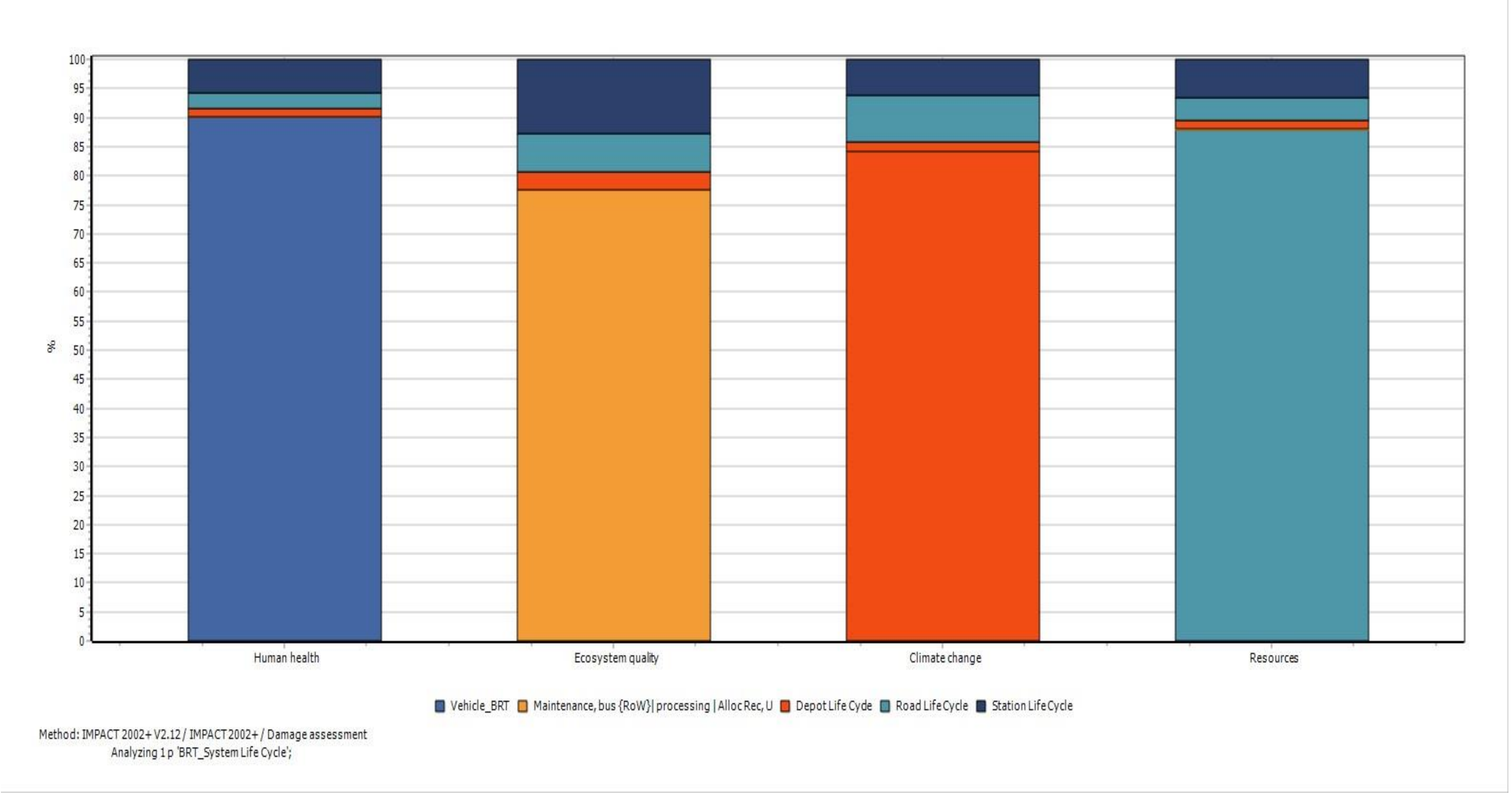


Figure 4-5. BRT, Base Case, Damage Assessment, Impact 2002+. (Simapro software)

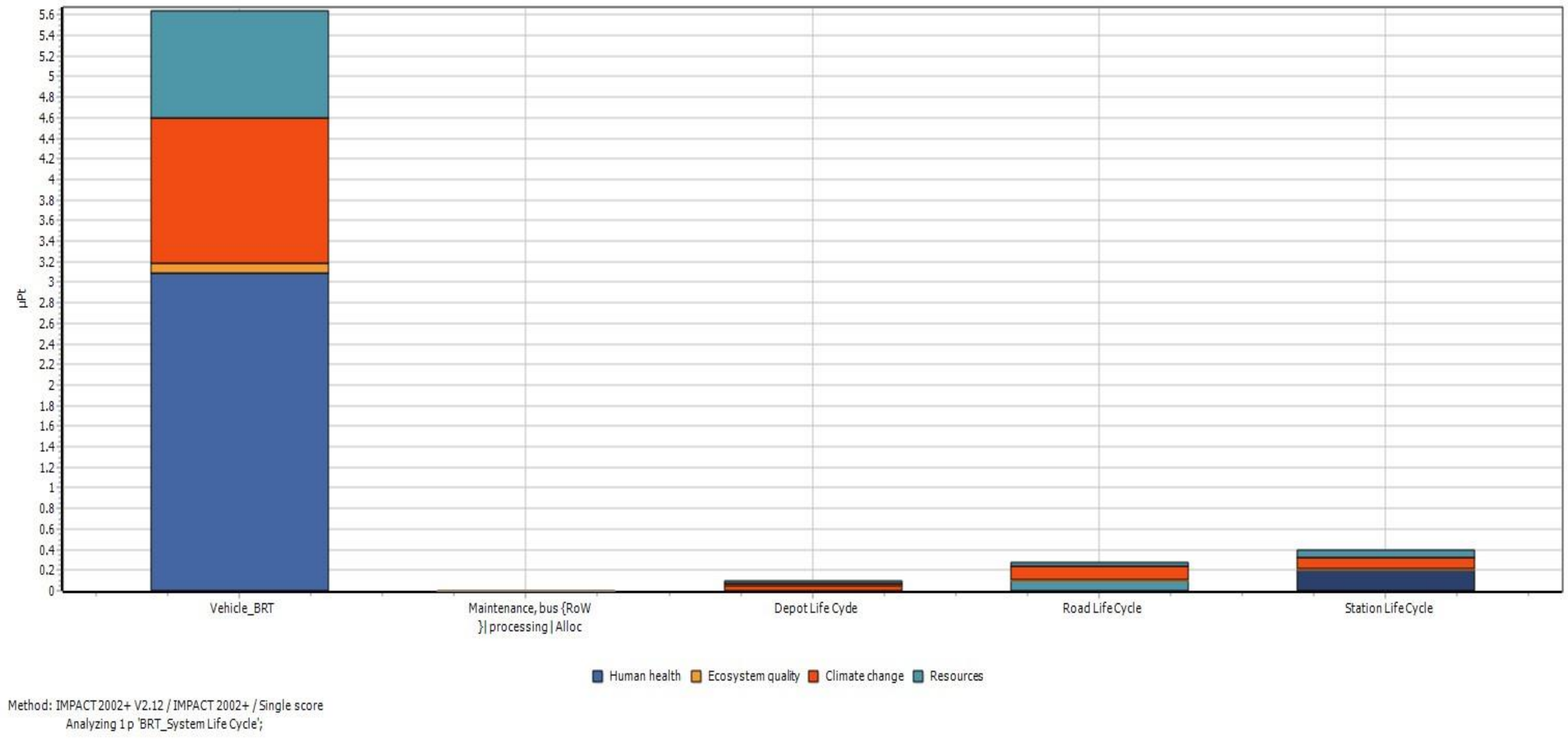


Figure 4-6. BRT, Base Case, Single Score, Impact 2002+ (Simapro software).

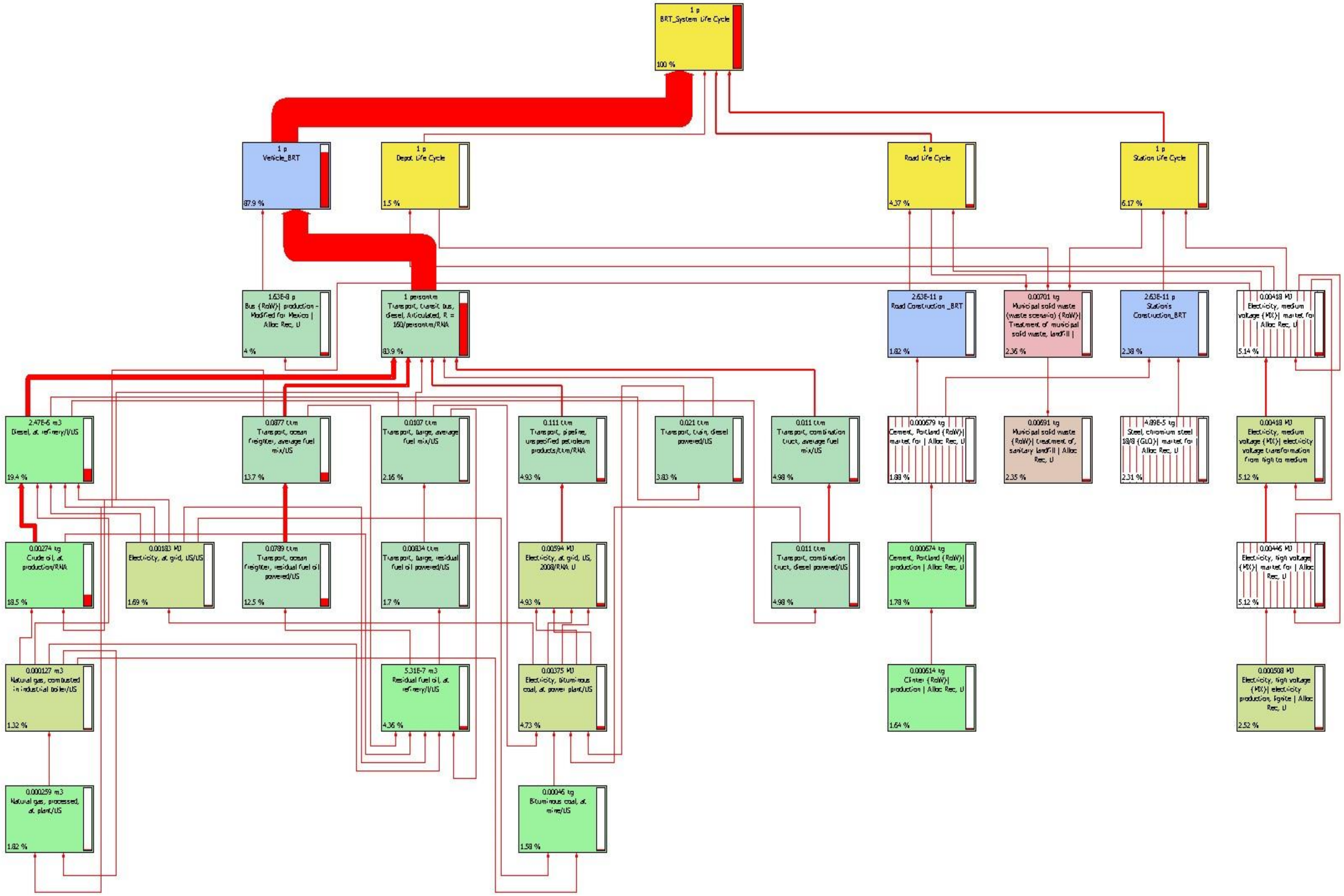


Figure 4-7. BRT, Base Case, Network Single Score at 5 % cut-off, Impact 2002+. (Simapro software).

Table 4-5. BRT, Damage Category, Impact 2002+.

Damage category	Unit	Total	Vehicle_BRT	Maintenance, bus {RoW}| processing | Alloc Rec, U	Depot Life Cycle	Road Life Cycle	Station Life Cycle	Vehicle (Bus) Percentage
Total	µPt	6.41	5.64	0.00071	0.0961	0.2801	0.396	87.95
Human health	µPt	3.42	3.09	0.000377	0.0448	0.0941	0.198	90.16
Ecosystem quality	µPt	0.125	0.097	1.56E-05	0.0039	0.0082	0.016	77.47
Climate change	µPt	1.68	1.41	0.000163	0.0281	0.1327	0.104	84.21
Resources	µPt	1.19	1.04	0.000155	0.0192	0.0451	0.079	87.95

Examination of the previous figures and table reveals that the greatest contributor to the BRT system, according to the Impact 2002+ method is the vehicle, consistently, with the station module in second place.

The next impact assessment method screened was Traci, which was run using its US 2008 option to perform the normalization step. Traci, as a midpoint and not an endpoint method, only has the characterization and normalization phases; it does not include any weighting, damage assessment or single score.

Figure 4-8 and Figure 4-9 show the results of Traci's characterization and normalization phases applied to the base case of the BRT. Although Traci's results do not reach the damage level, it is also clear that according to this method, the vehicle subsystem has the greatest impact in all categories, but interestingly, the second place in terms of impact belongs to the road module in this method.

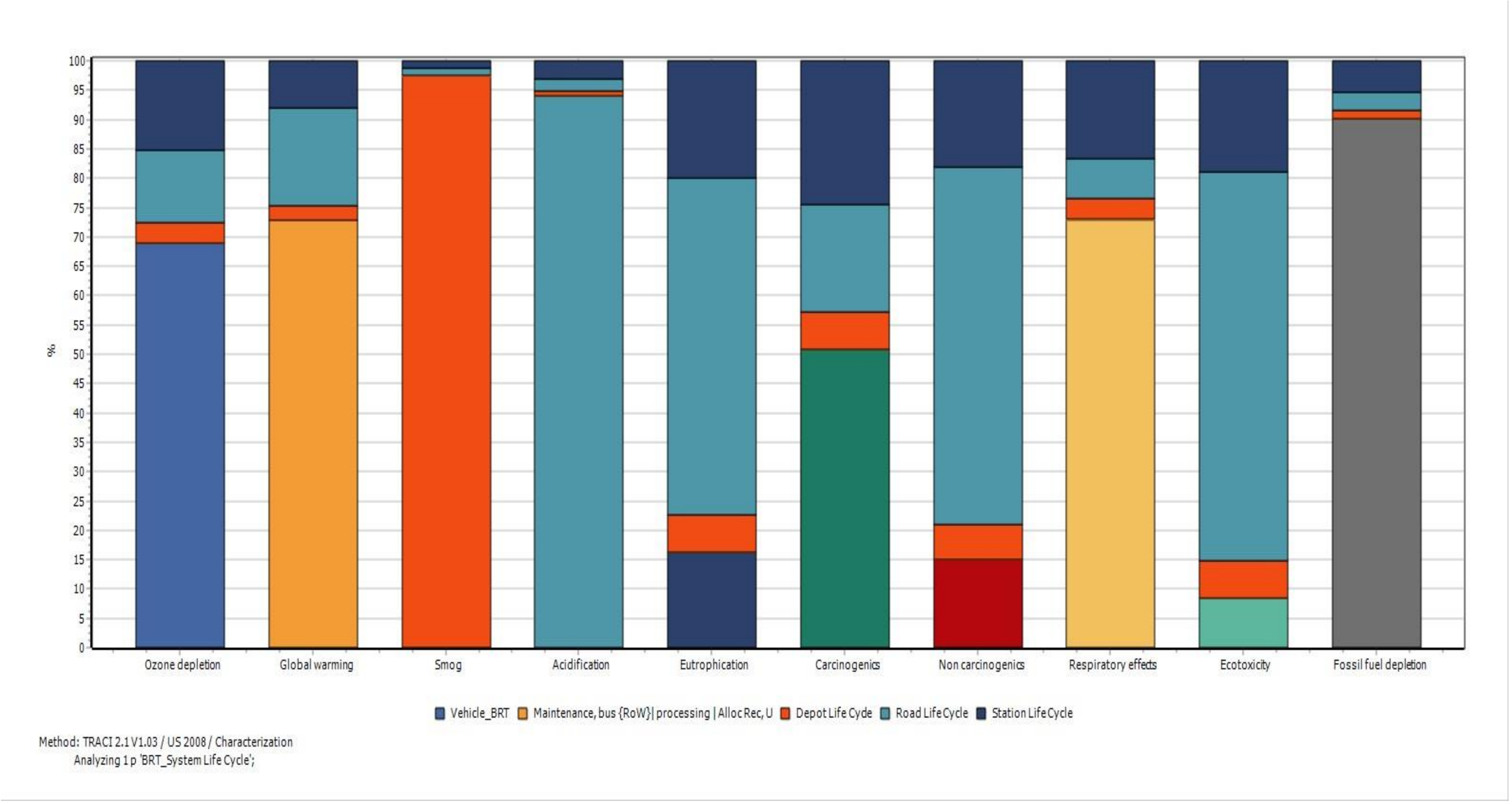
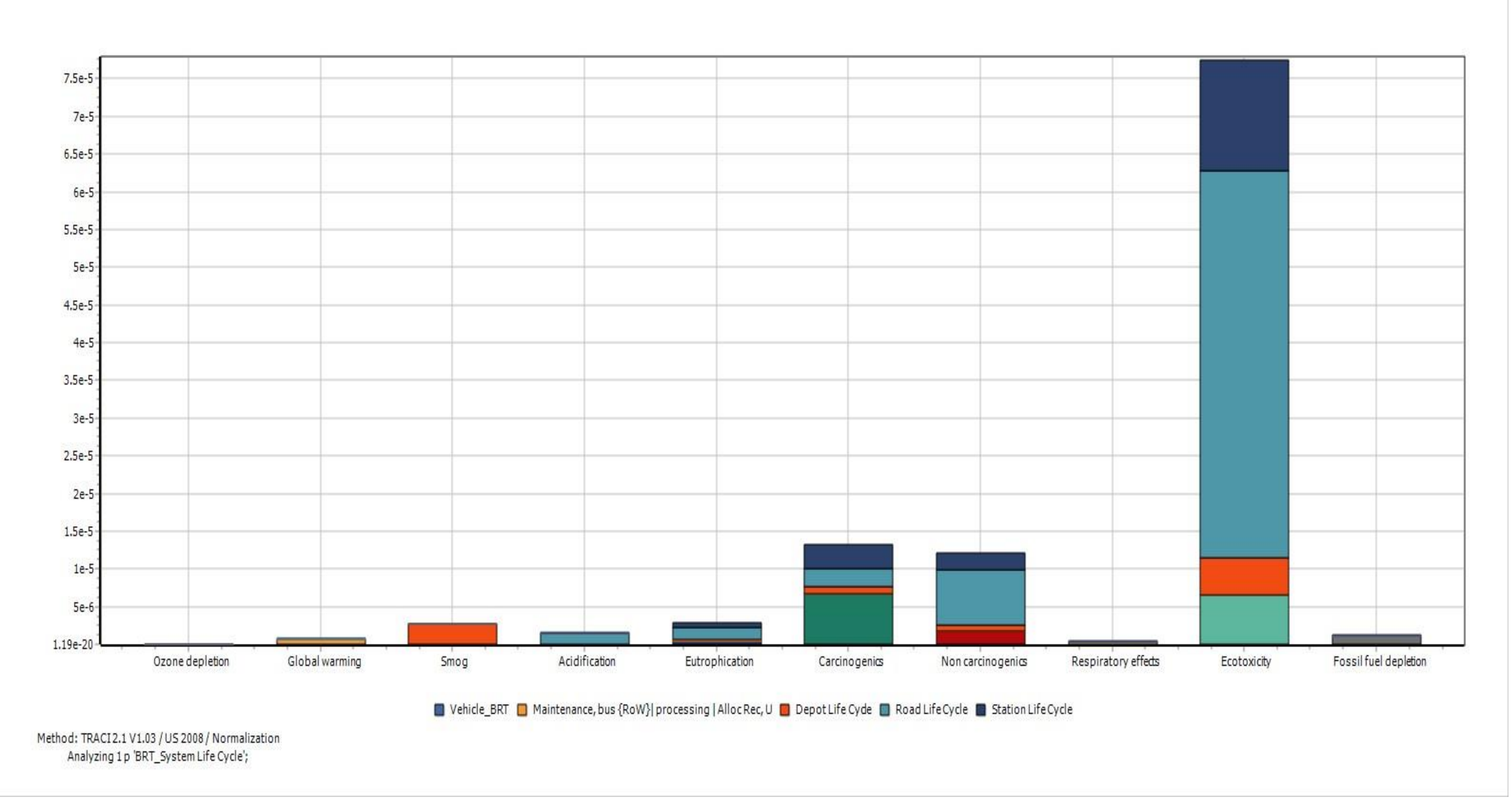


Figure 4-8. BRT, Base Case, Characterization, Traci. (Simapro Software).



Method: TRACI 2.1 V1.03 / US 2008 / Normalization
Analyzing 1 p 'BRT_System Life Cycle';

Figure 4-9. BRT, Base Case, Normalization, Traci (Simapro software).

4.1.4 Initial Screening for Private Car

Similarly, once the car with its infrastructure, energy and vehicle subsystems was built, an initial screening was conducted, both to choose the most apropos Impact Assessment (EIA) method and to obtain a sense of the behaviour of the system.

An initial screening of the inventory results for the car is shown in Table 4-6, where the percentages of each module or subsystem have been added as the last three columns. As expected, the vehicle subsystem generates the vast majority of nitrogen oxides - which result from fuel combustion - and of carbon dioxide emissions. An interesting result, which is in line with previous studies (Chester, 2009, 2010), is that the contribution of the infrastructure, in this case, the road, to the inventory of $PM_{2.5}$ is significant. For the base case of the car, $PM_{2.5}$ from the road is a staggering 51.97% of the total inventory, which is more than seven times the amount resulting only from “Transport,” the car’s operation.

Figure 4-10 to Figure 4-14 show the results of applying the Impact 2002+ method to the Base Case of the car. In this instance, the Base Case was defined as a car with a lifetime of 15 years, which is the average lifetime in Mexico City (SEMOVI, 2013), with an expected lifetime VKT of 187,500 kms, and a ridership of 1.7 passengers.

As can be observed in these figures, the vehicle subsystem is the one with the greatest impacts, in all categories. However, it is interesting to note, particularly in Figure 4-11 and in Figure 4-14, that according to this method, it is the human health category the one with the greatest impacts, even surpassing the climate change category, as would probably be the first expectation. In fact, it is the resources category that follows in the second place of impacts, and the climate change category is the third place, with the ecosystem quality impact category once again in a very distant fourth place.

Figure 4-15 shows that in the Single Score phase of this method, the contribution of Vehicle Manufacturing and Maintenance is 17.5%; the Transport module within Simapro, representing the energy subsystem of the vehicle, its actual operation, accounts for 62.6% and the Road module is 19.8%. This result ratifies initially one of the major assumptions of this study, namely, that the infrastructure subsystem has a significant contribution to the impacts of any transportation mode, and thus, infrastructure should be included in a true life-cycle perspective.

Table 4-6. Selected LCI Results for Car.

Impact category	Unit	Total	Vehicle Manufacturing and Maintenance	Transport, passenger car, gasoline, R = 1.7 /personkm/RNA	Road Life Cycle - R1.7	Manufacturing and Maintenance Percentage	Transport Percentage	Road Percentage
NMVOC	kg	0.000203	6.93E-05	0.000109	2.50E-05	34.09%	53.62%	12.29%
Carbon dioxide, fossil	kg	0.221	0.0292	0.164	0.0280	13.20%	74.12%	12.68%
Sulphur dioxide	kg	0.000344	0.000126	0.000102	0.000116	36.82%	29.55%	33.63%
Nitrogen oxides	kg	0.000676	6.96E-05	0.000533	7.26E-05	10.31%	78.95%	10.75%
Particulates, <2.5 µm	kg	9.22E-05	3.76E-05	6.67E-06	4.79E-05	40.80%	7.23%	51.97%
Land occupation	m^2a	0.00267	0.00184	0	0.000831	68.86%	0.00%	31.14%
BOD	kg	0.000115	4.52E-05	3.57E-05	3.42E-05	39.26%	31.01%	29.72%
Cadmium	kg	3.83E-11	2.10E-11	0	1.72E-11	54.86%	0.00%	45.14%

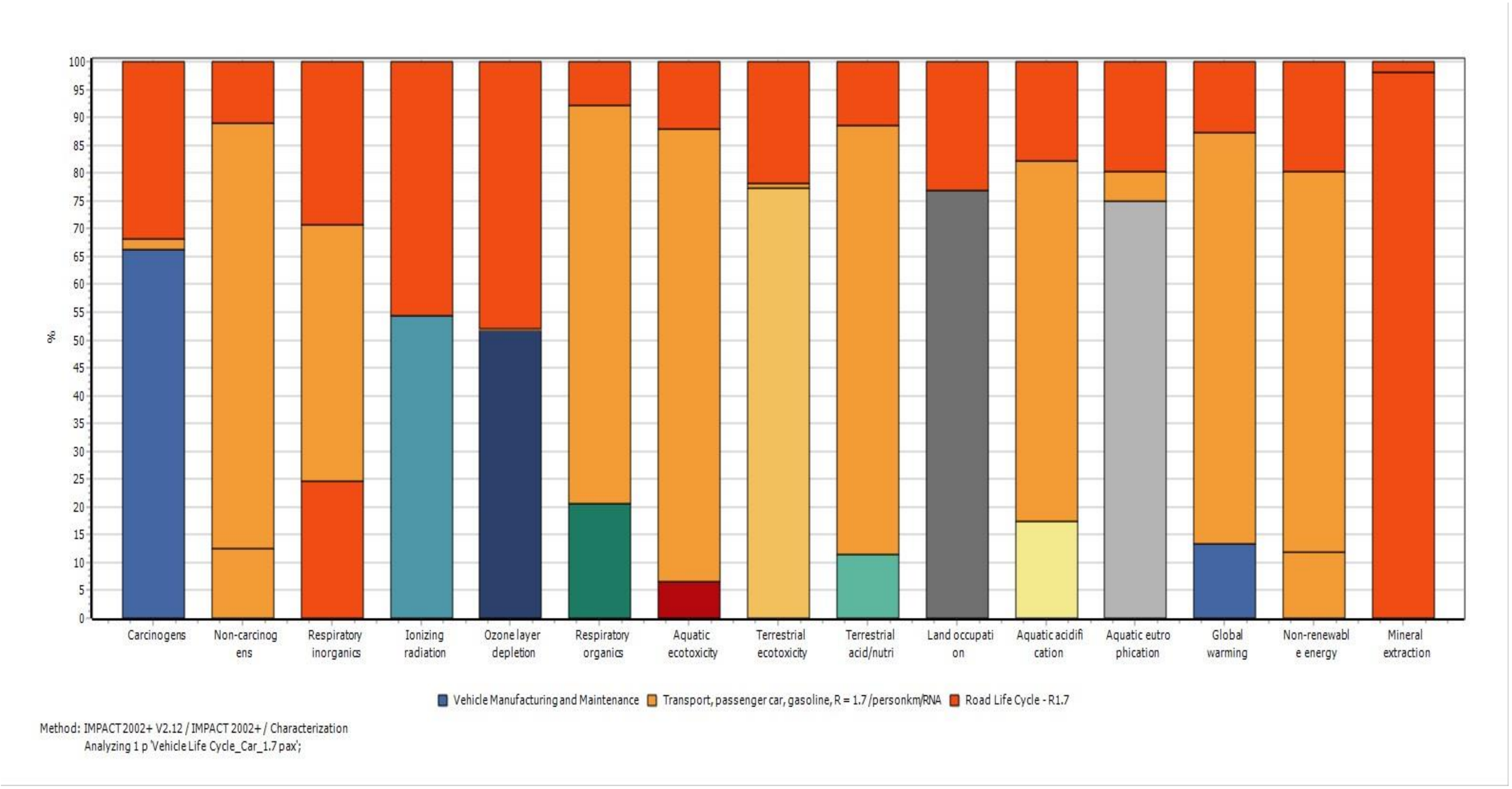


Figure 4-10. Car, Base Case, Characterization, Impact 2002+ (Simapro software).

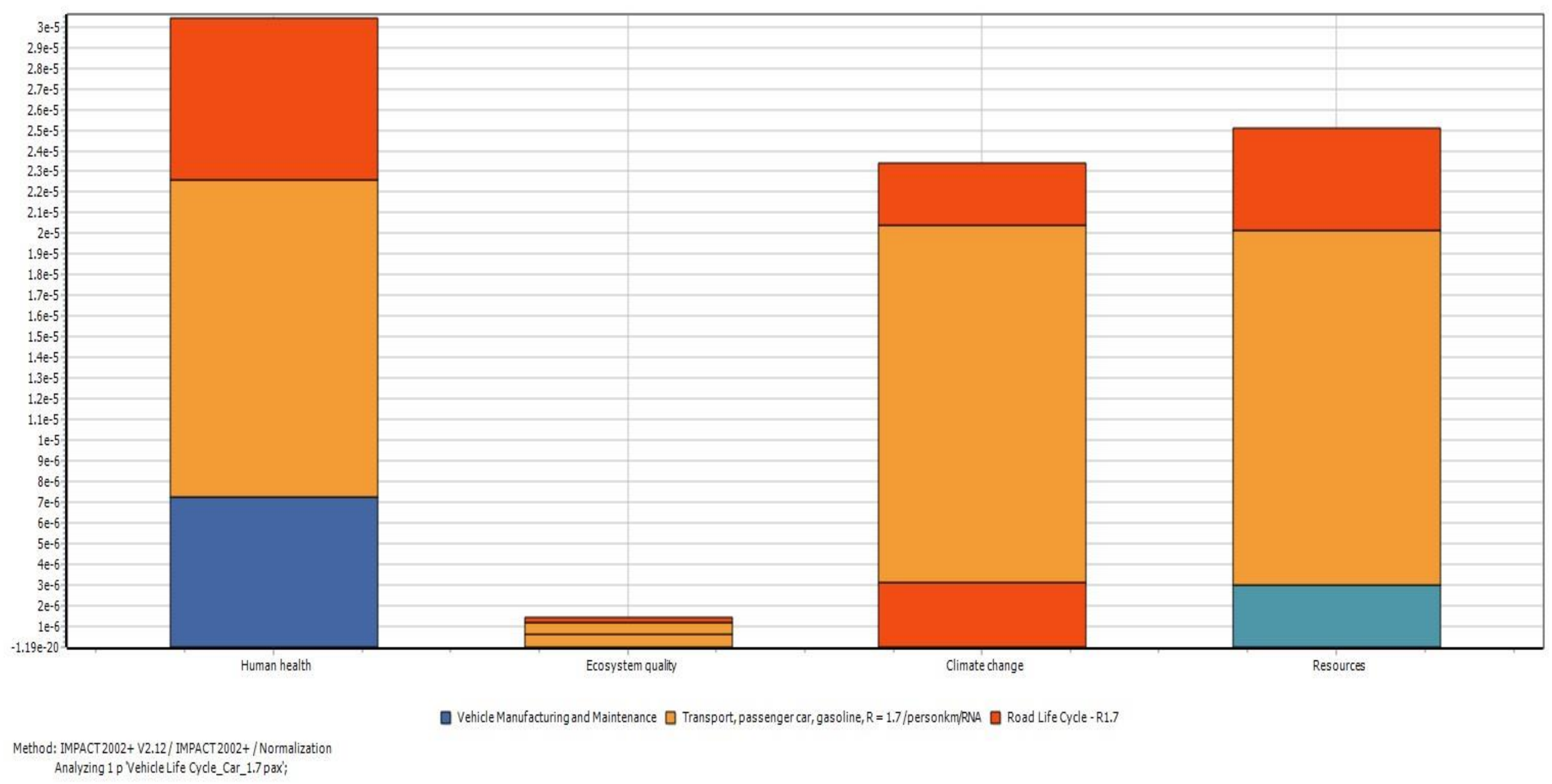


Figure 4-11. Car, Base Case, Normalization, Impact 2002+ (Simapro software).

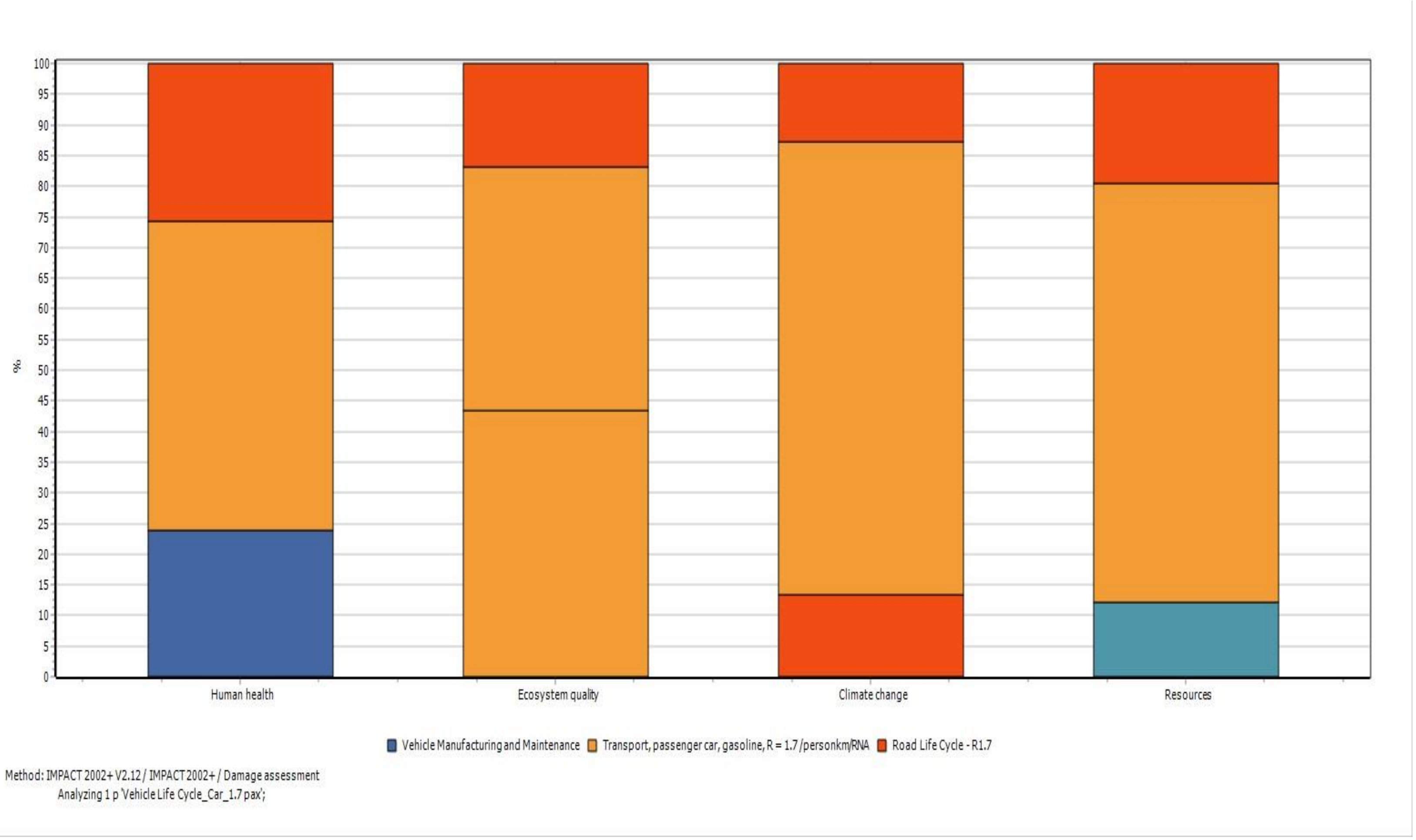


Figure 4-12. Car, Base Case, Damage Assessment, Impact 2002+ (Simapro software).

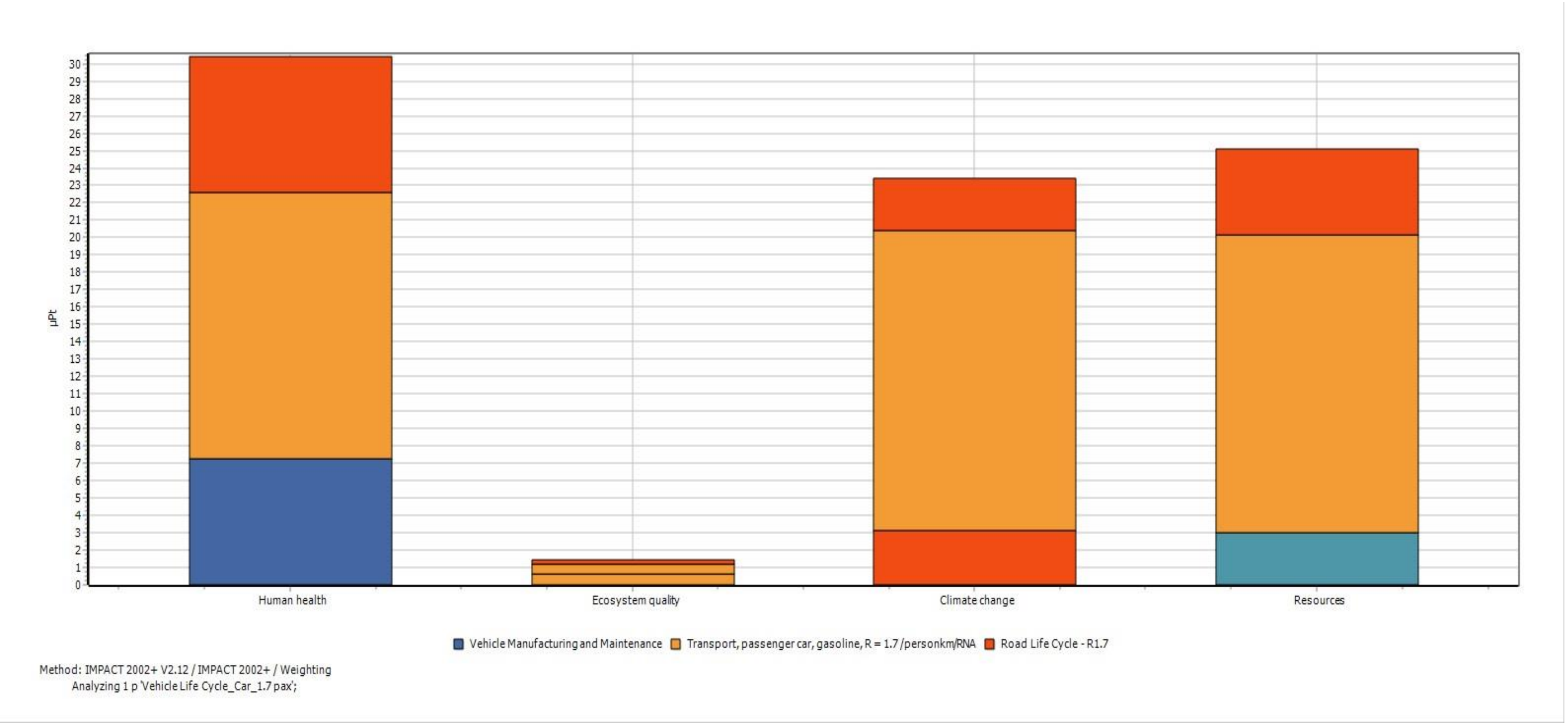


Figure 4-13. Car, Base Case, Weighting, Impact 2002+ (Simapro software).

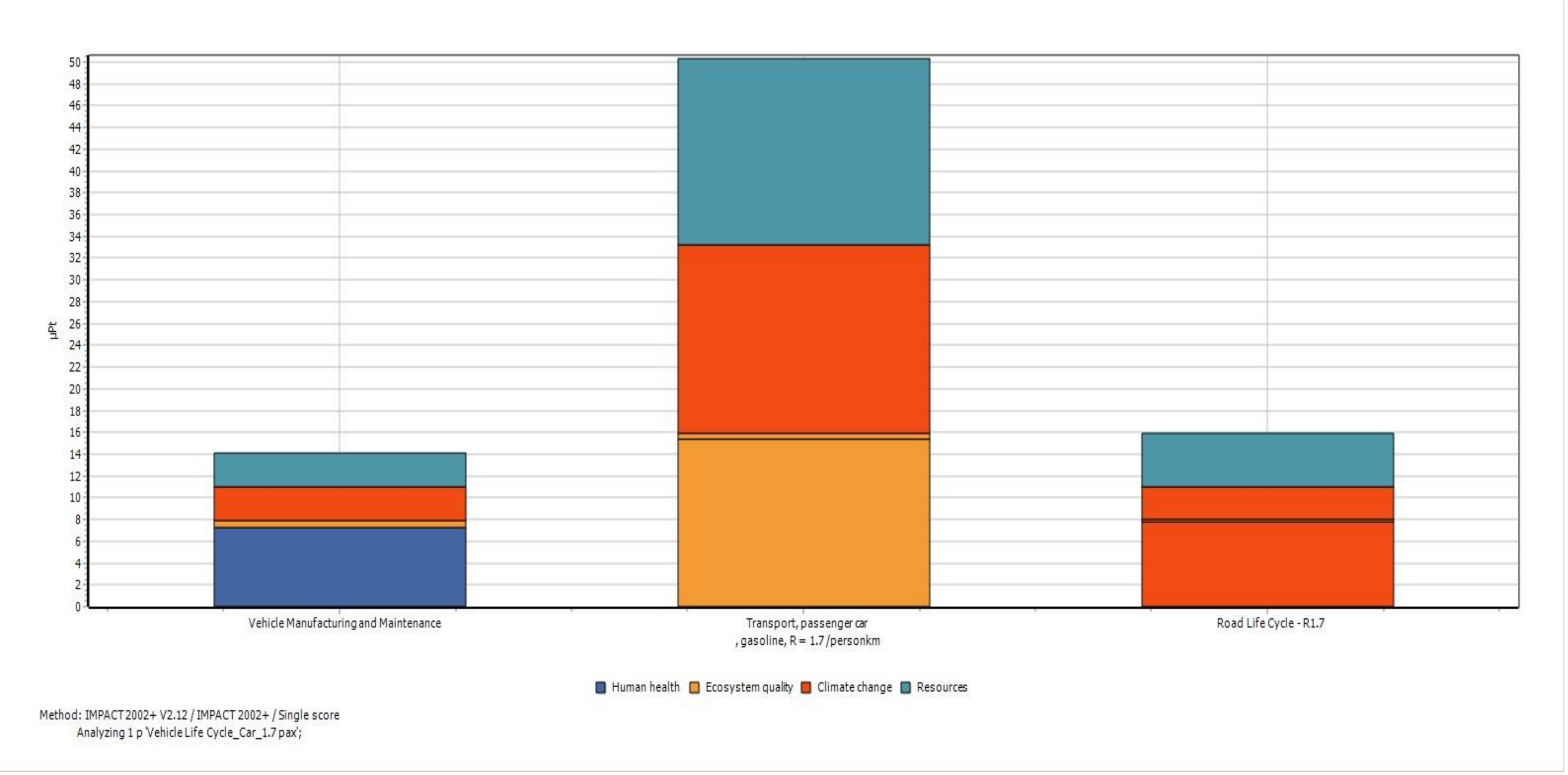


Figure 4-14. Car, Base Case, Single Score, Impact 2002+ (Simapro software).

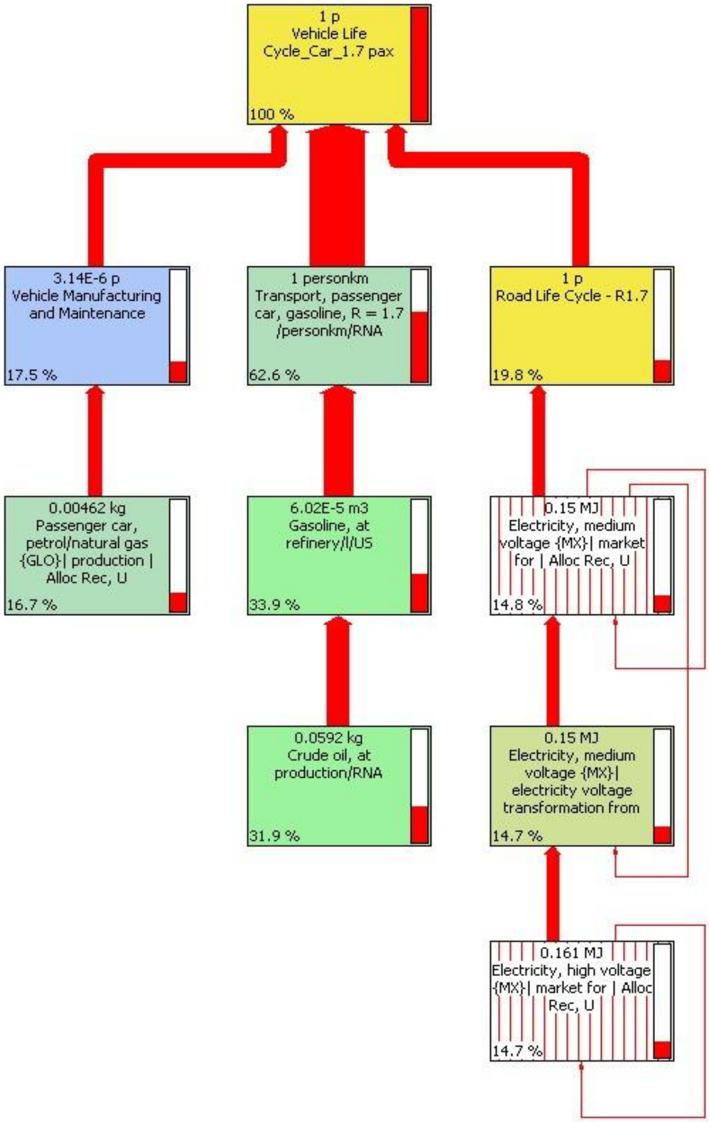


Figure 4-15. Car, Base Case, Network Single Score, Impact 2002+ (Simapro software).

The car was also initially screened using the Traci midpoint method. Figure 4-16 shows the result of the characterization phase of the Traci method. To note, the vehicle’s manufacturing and maintenance has an important impact in the Eutrophication and Ecotoxicity categories, most probably due to the effect of the transmission, engine, brake and wiper fluids upon water quality. It is also important to note the contribution of the road life cycle to the fossil fuel impact category in the Traci method, which even at the characterization phase appears significant. To further explore how significant this contribution was, Figure 4-17 shows that in the characterization phase, for the fossil fuel depletion category under the Traci method, the vehicle’s manufacturing and maintenance is 7.24% of the total impact; the “transport,” or vehicle operation and fuel combustion is 73.4% and the road’s life cycle represents 19.4% of the total. This latter percentage is probably due to the hours of operation of the machinery for the initial building of the road, but also includes the continual resurfacing of the asphaltic pavement, which was duly accounted for in the setting up of the road subsystem. In this method, as with all preceding methods, the vehicle operation is the greatest generator of impact, in all categories.

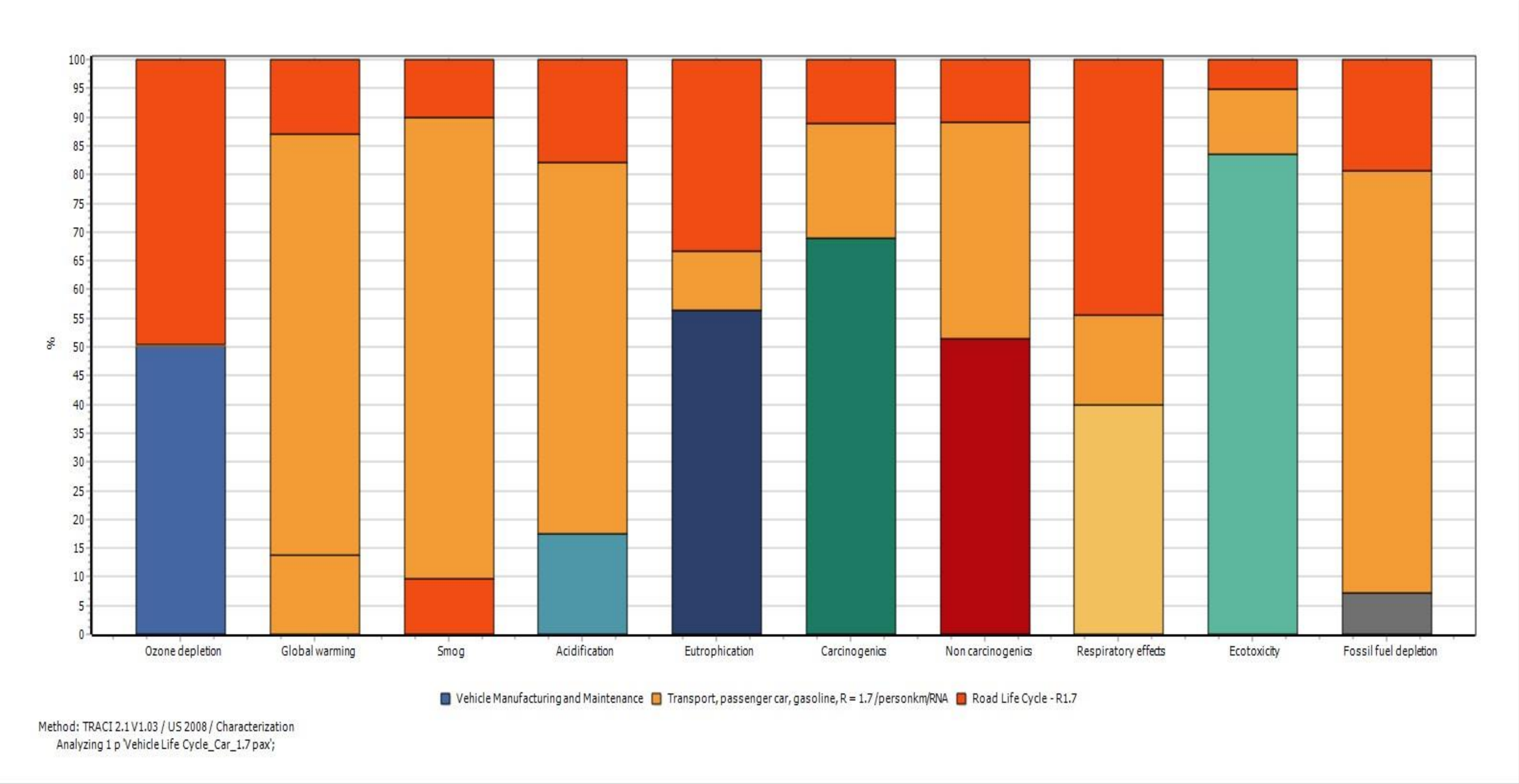


Figure 4-16. Car, Base Case, Characterization, Traci (Simapro software).

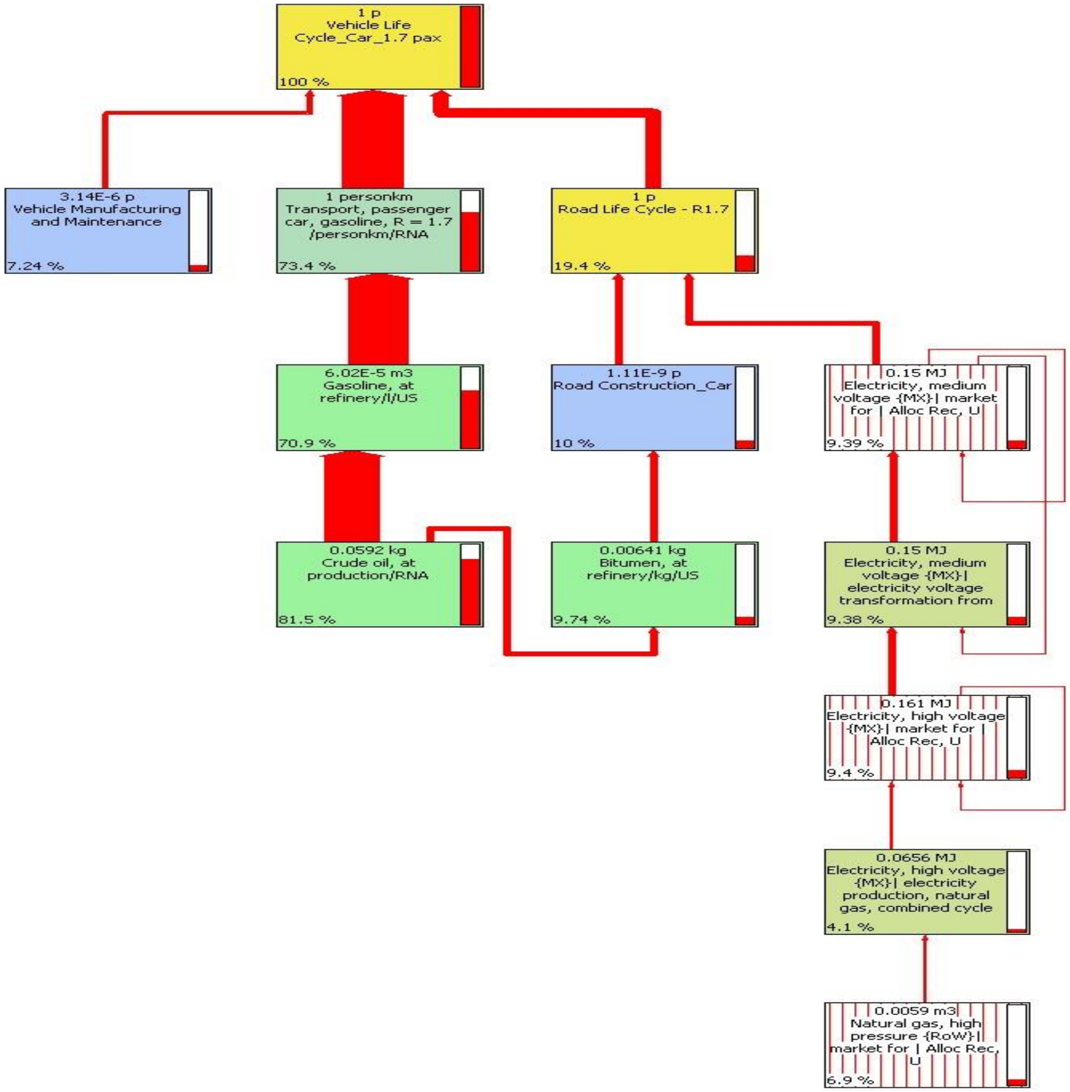


Figure 4-17. Car, Base Case, Network for Characterization, Fossil Fuel Depletion Category, Traci (Simapro software).

4.1.5 Initial Screening for Subway

Following the procedure for the previous BRT and Private Car LCAs, once the Subway system was built an initial screening was performed. Figure 4-18 presents the results at the characterization phase of the initial screening for the subway's base case. From this and succeeding figures, it was clear from the outset that for the subway the greatest generator, by a large margin, of air pollutants and other emissions to all media (soil, water, air) was the electricity used to run the trains.

The base case for the subway was defined as a train with a lifetime of 33 years, with a peak ridership of 1,530 passengers, operating 387 kilometers per day, during 300 years per year, for an annual VKT of approximately 116,100 kilometers and a $VKT_{LIFETIME}$ = 3' 831, 300 kilometers.

Table 4-7 presents the results, at the inventory level, of the initial screening for the subway, along with the total and subtotal amounts for each subsystem. Additionally, this table has the percentages corresponding to the subway subsystems for each of these selected pollutants and emissions. In all cases, the vehicle operation generates over 97% of the inventory. It must be noted that while the air pollutants generated by this subway system in a passenger-kilometer basis are low, and as will be seen later, the lowest among the three modes analyzed for this dissertation, they are nevertheless existent, and for all practical purposes they are attributable almost solely to the train operation.

The fact that the life cycle is dominated by the use phase, or the vehicle operation (the "Transport, passenger train" product stage within Simapro in this LCA) is consistent with all previous studies (Chester, 2009; Del Pero, 2015). In fact, for the Roman Metro's Line C. Environmental Product Declaration (EPD), for an Ansaldo Breda train, it was reported that the use phase accounts for around 92% of the total energy consumption. In this case, it was assumed that the Metro Roma C electricity consumption is 17.83 kWh per kilometer, with the Italian electricity mix. The number of passengers used for this EPD was 1,204. This specific case of the Roma C Metro provides a robust point of comparison to Mexico City's subway, since previous studies (Santoyo-Castelazo, 2011) have proven the strong correlation between the Mexican and Italian electricity mixes, among others.

Another interesting observation can be made from Table 4-7, upon examination of the relative percentages to land occupation of all subsystems. While all infrastructure modules are low, it is the life cycle of the railway track module the one that results with the highest percentage, 0.70% in the land occupation category, even on top of the station and the depot. This is also in line with previous studies (Tuschmid, 2011), where the lifetime impact of the railway surpasses that of the buildings.

The subway system was screened next with the Impact 2002+ method. Figure 4-19 to Figure 4-23 show the characterization, damage assessment, normalization, weighting and single score phases, respectively, of applying the Impact 2002+ to the subway's base case. Particularly from Figure 4-21 and Figure 4-22, it can be observed that according to the present EIA method, the subway's impacts are mostly in the human health category, followed in approximately an equal amount by the categories of climate change and resources, with the ecosystem quality impact category in fourth place again. Thus, we see that for all three modes of transportation assessed in this study, according to the Impact 2002+ method, the human health category had the greatest impacts, with the Resources category in second place, and a close third place for climate change (or tied in the second place with the resources category, in the case of the subway). In all cases the ecosystem quality category had a much lower impact, thus making it reasonable to assume that the Impact 2002+ method would assess any transportation mode in approximately the same way across the impact categories.

Figure 4-24 presents the network diagram for the single score phase of the Impact 2002+ of the subway's base case. This diagram shows that the "transport" or vehicle operation portion of the subway accounts for 98.5% of the total system's impact. Of this impact, 82.3% comes from the electricity used to power the train, while 16% corresponds to the maintenance of the train. To provide perspective, the "major maintenance" services, where the train is disassembled, cleaned, and occasionally, the bogies are replaced, etc., are scheduled for every 700,000 kilometers travelled. Hence, an average train will have between five or six of these "major maintenance" services throughout its lifetime.

Table 4-8 shows the results for each of the subsystems in each impact category, according to the Impact 2002+ method, as well as their percentage contributions to the total amount. To note, these figures represent impact, measured in µPt, not inventory results. That is, these numbers have gone through the valuation (normalization and weighting) process of the Impact 2002+. In this table, the railway life cycle has the greatest impact, among the infrastructure modules, and the station is the greatest contributor to climate change. As usual, the vehicle operation represents more than 96% of the impact in all categories.

The subway system was also screened using the Traci method. Figure 4-25 shows the results of the characterization phase, and Figure 4-26 of the normalization phase of the Traci method. Examination of this latter figure indicates that, according to the midpoint Traci method, the carcinogenics category is the one with the greatest impact, followed by the ecotoxicity, eutrophication and non-carcinogenics categories, respectively, and the fossil fuel depletion category appears only in the fifth place of categories with the most impact.

Further analyzing the fossil fuel depletion category, Figure 4-27 presents the network diagram for the characterization phase of this category. This shows that the vehicle operation is responsible for 98.6% of the impact, and of this number, 85.1% corresponds to the electricity and 13.6% to the train's maintenance. This again confirms the results from previous methods, showing only slight variations in the percentages from one method to the next, but ratifying the underlying trend.

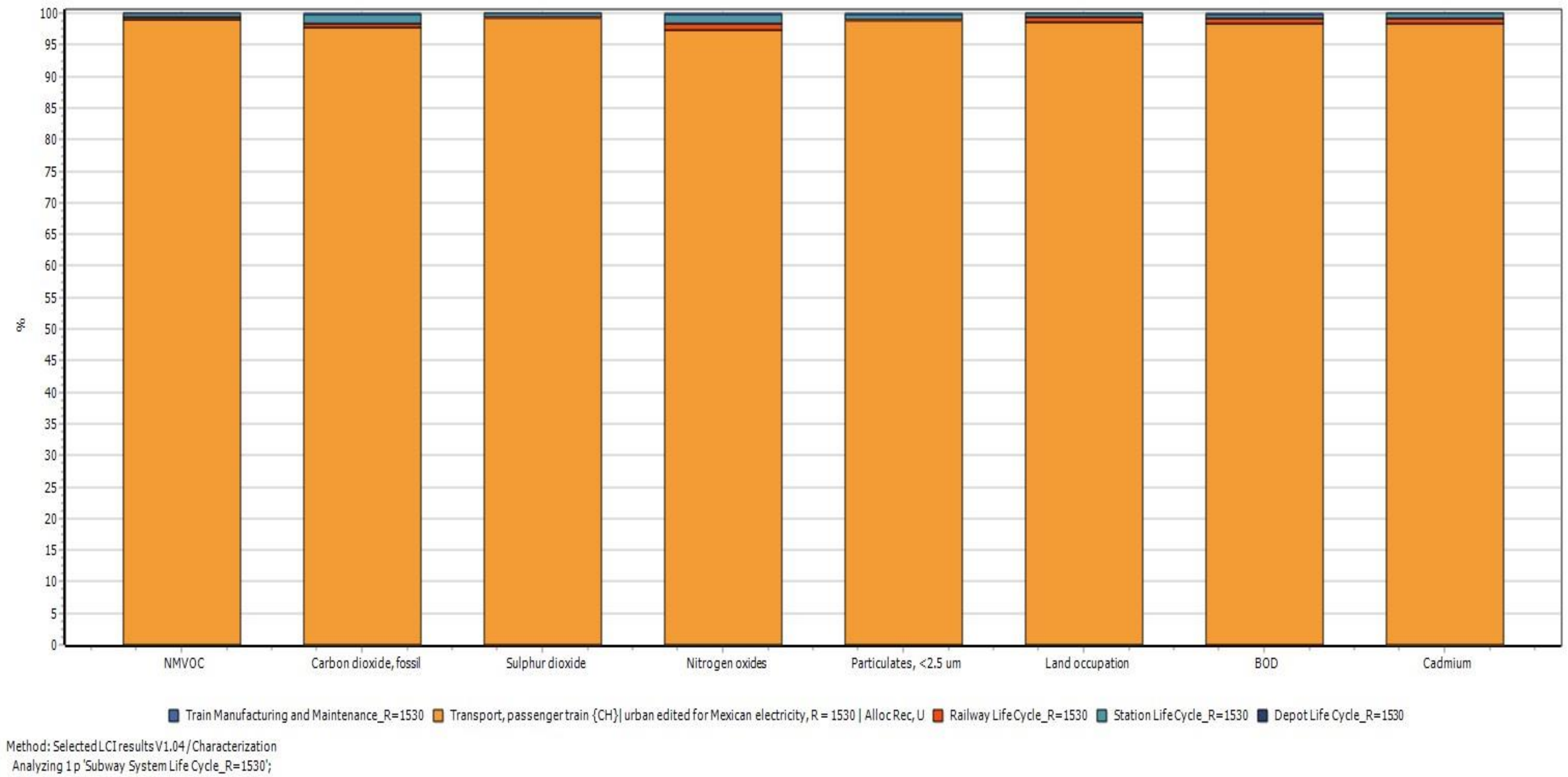


Figure 4-18. Subway, Base Case, Characterization, Selected LCI Results (Simapro software).

Table 4-7. Selected LCI Results for Subway

Impact category	Unit	Total	Train Manuf. & Maint. R=1530	Transport, passenger train, urban edited for Mexican electricity, R = 1530 | Alloc Rec, U	Railway Life Cycle R=1530	Station Life Cycle R=1530	Depot Life Cycle R=1530	Vehicle Operation Percentage	Railway Percentage	Station Percentage	Depot Percentage
NMVOC	kg	7.614E-06	1.078E-18	7.533E-06	3.8573E-08	3.671E-08	5.792E-09	98.94%	0.51%	0.48%	0.08%
Carbon dioxide, fossil	kg	0.009278	6.671E-16	0.009067	5.349E-05	0.0001363	2.135E-05	97.72%	0.58%	1.47%	0.23%
Sulphur dioxide	kg	3.822E-05	3.921E-18	3.789E-05	1.110E-07	1.965E-07	3.102E-08	99.11%	0.29%	0.51%	0.08%
Nitrogen oxides	kg	1.881E-05	1.871E-18	1.833E-05	1.819E-07	2.629E-07	4.087E-08	97.42%	0.97%	1.40%	0.22%
Particulates, <2.5 µm	kg	1.622E-05	8.459E-19	1.603E-05	3.767E-08	1.358E-07	2.209-08	98.79%	0.23%	0.84%	0.14%
Land occupation	m^2a	0.0004412	3.715E-16	0.0004351	3.081E-06	2.623E-06	4.076E-07	98.61%	0.70%	0.59%	0.09%
BOD	kg	1.081E-05	1.128E-18	1.064E-05	7.523E-08	8.056E-08	1.242E-08	98.44%	0.70%	0.75%	0.11%
Cadmium	kg	9.722E-12	7.493E-24	9.570E-12	8.100E-14	6.067E-14	9.419E-15	98.45%	0.83%	0.62%	0.10%

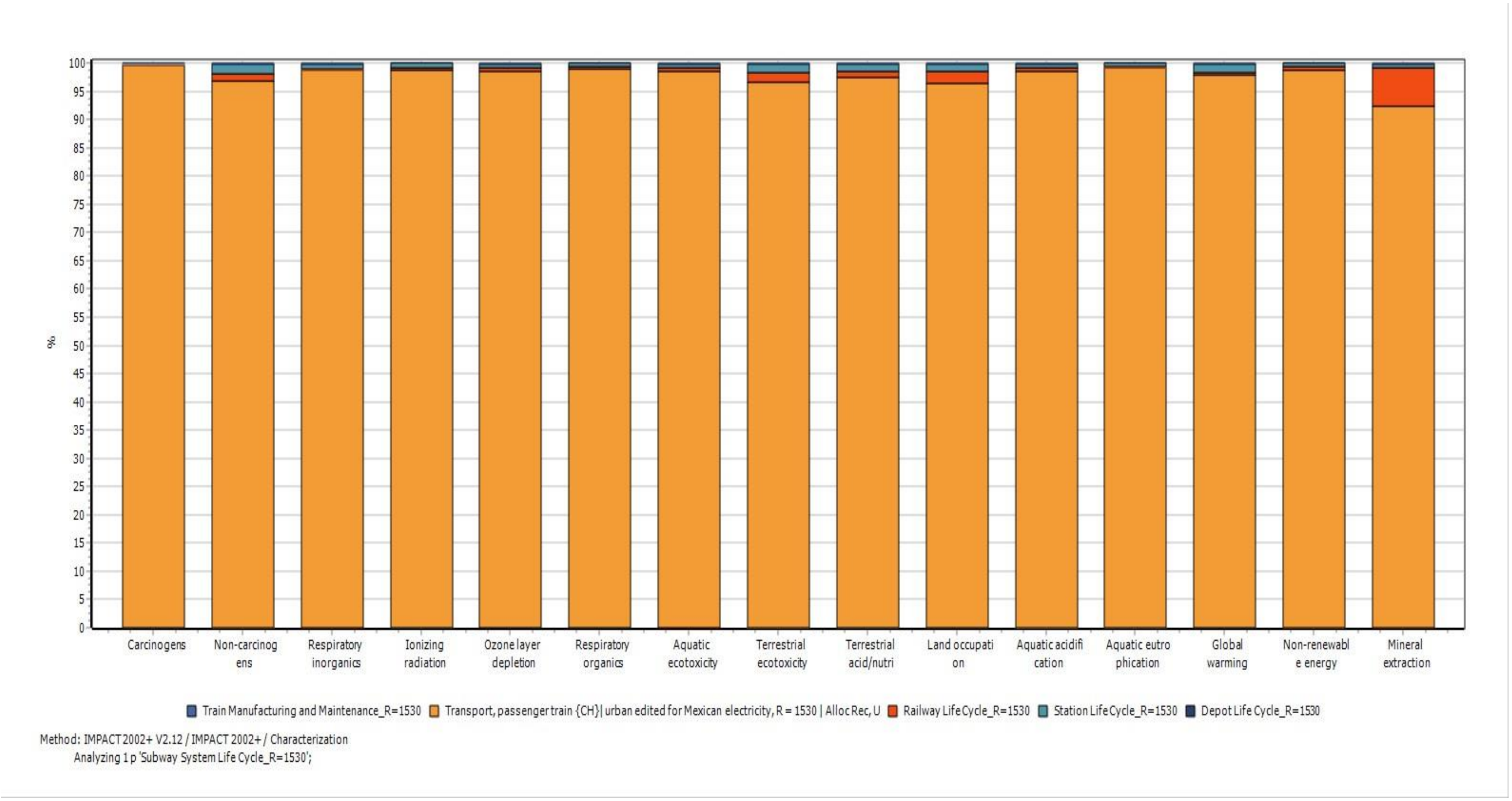


Figure 4-19. Subway, Base Case, Characterization, Impact 2002+ (Simapro software).

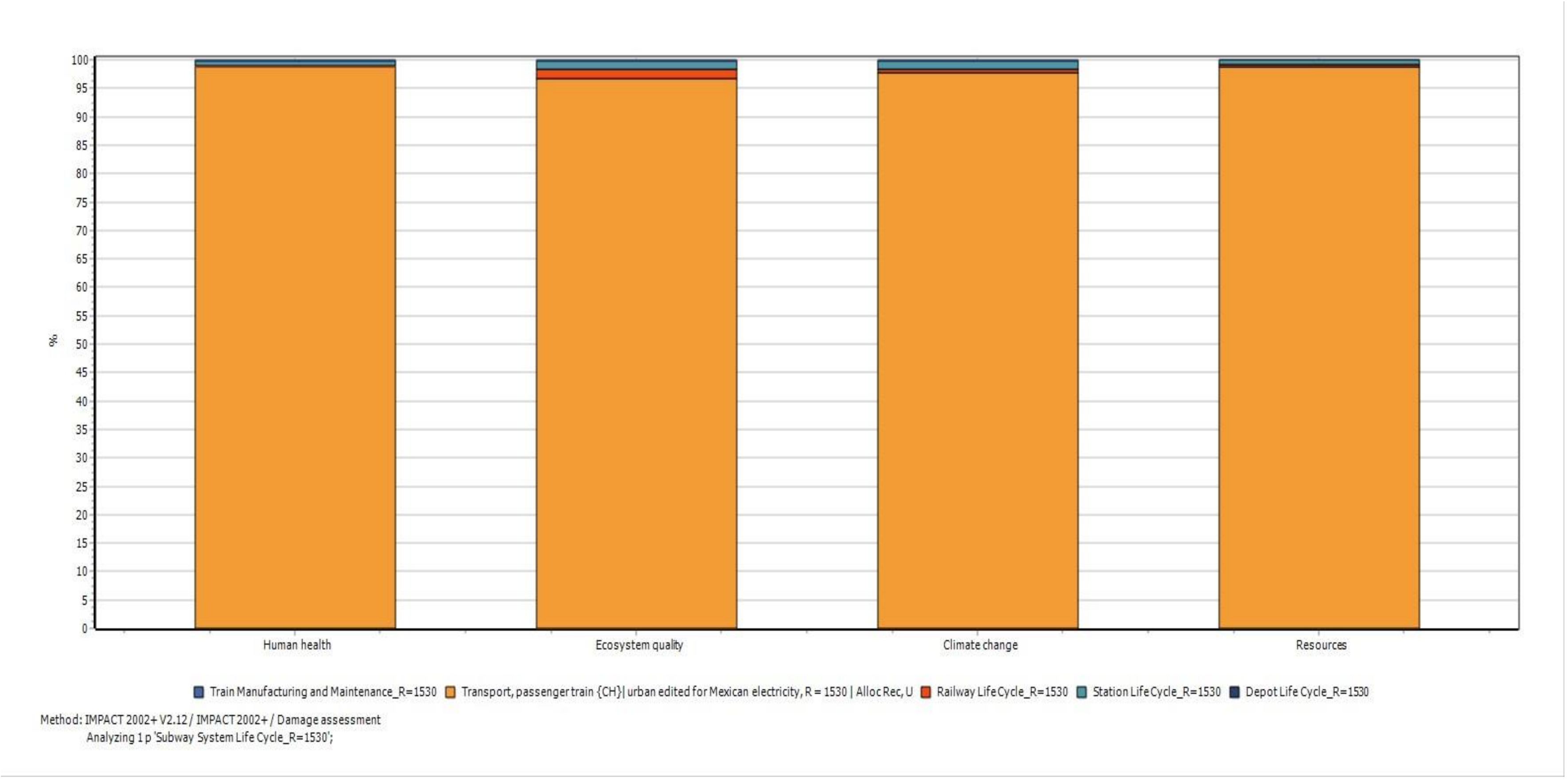
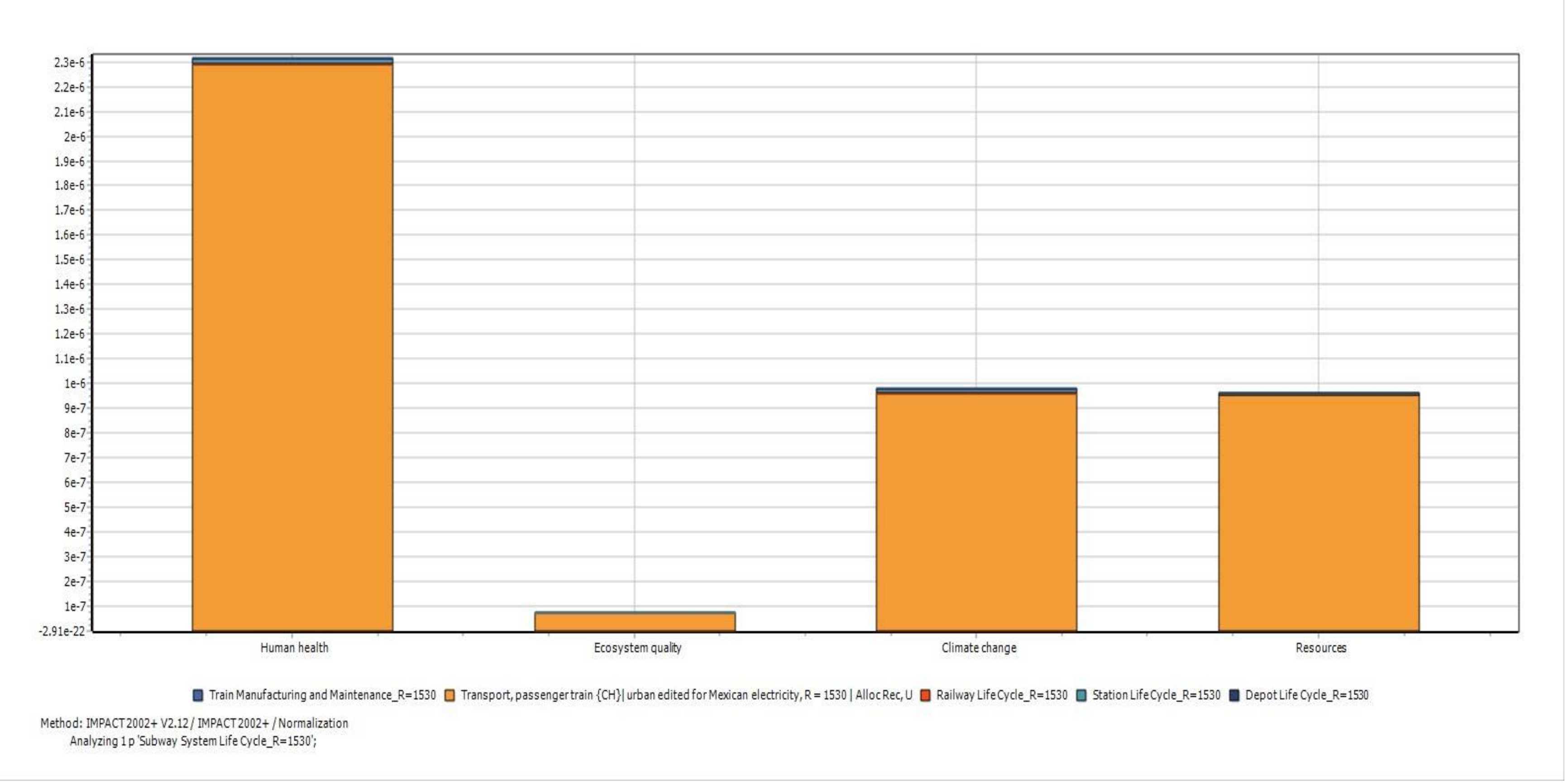


Figure 4-20. Subway, Base Case, Damage Assessment, Impact 2002+ (Simapro software).



Method: IMPACT 2002+ V2.12 / IMPACT 2002+ / Normalization
Analyzing 1 p 'Subway System Life Cycle_R=1530';

Figure 4-21. Subway, Base Case, Normalization, Impact 2002+ (Simapro software).

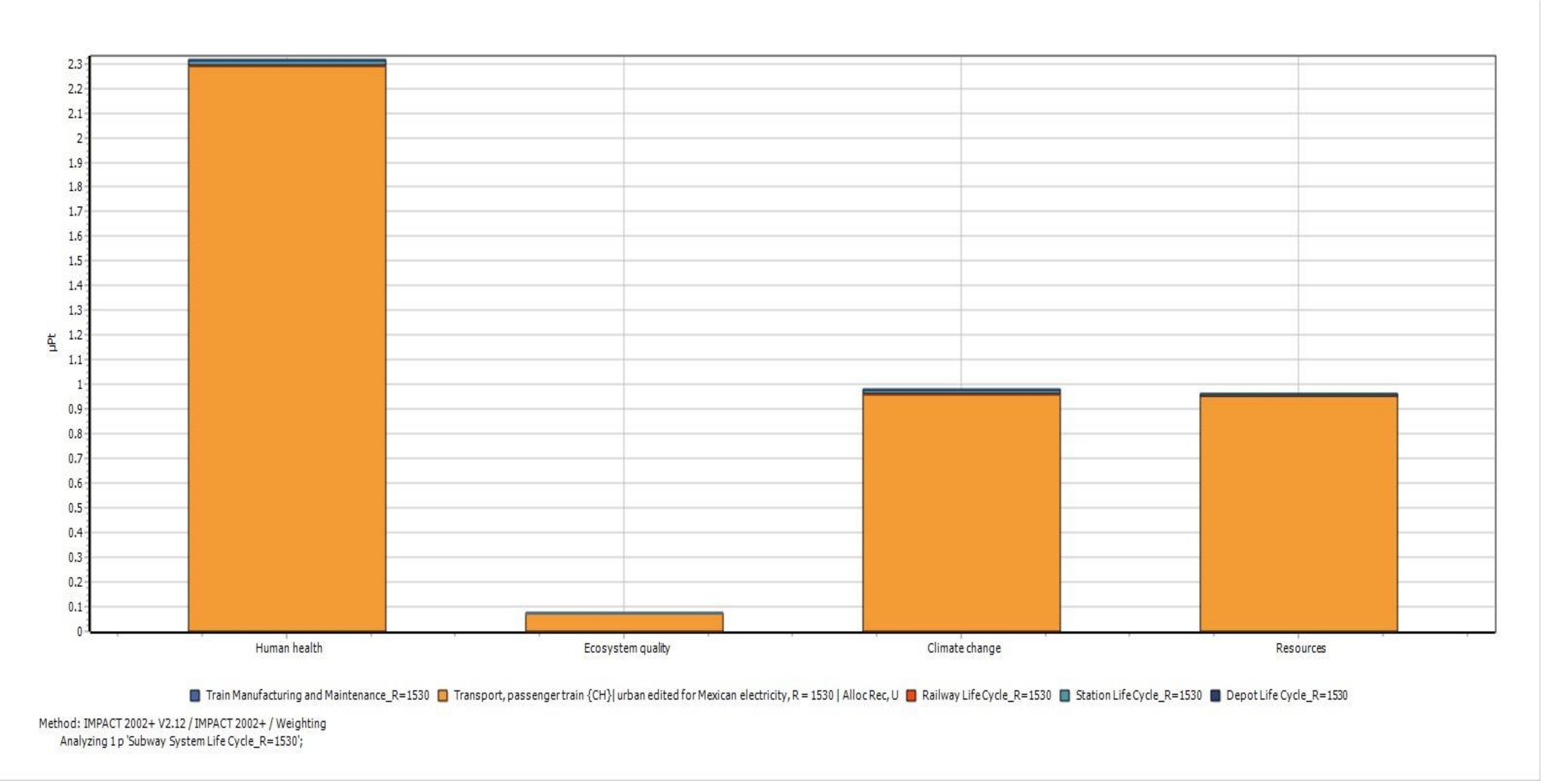


Figure 4-22. Subway, Base Case, Weighting, Impact 2002+ (Simapro software).

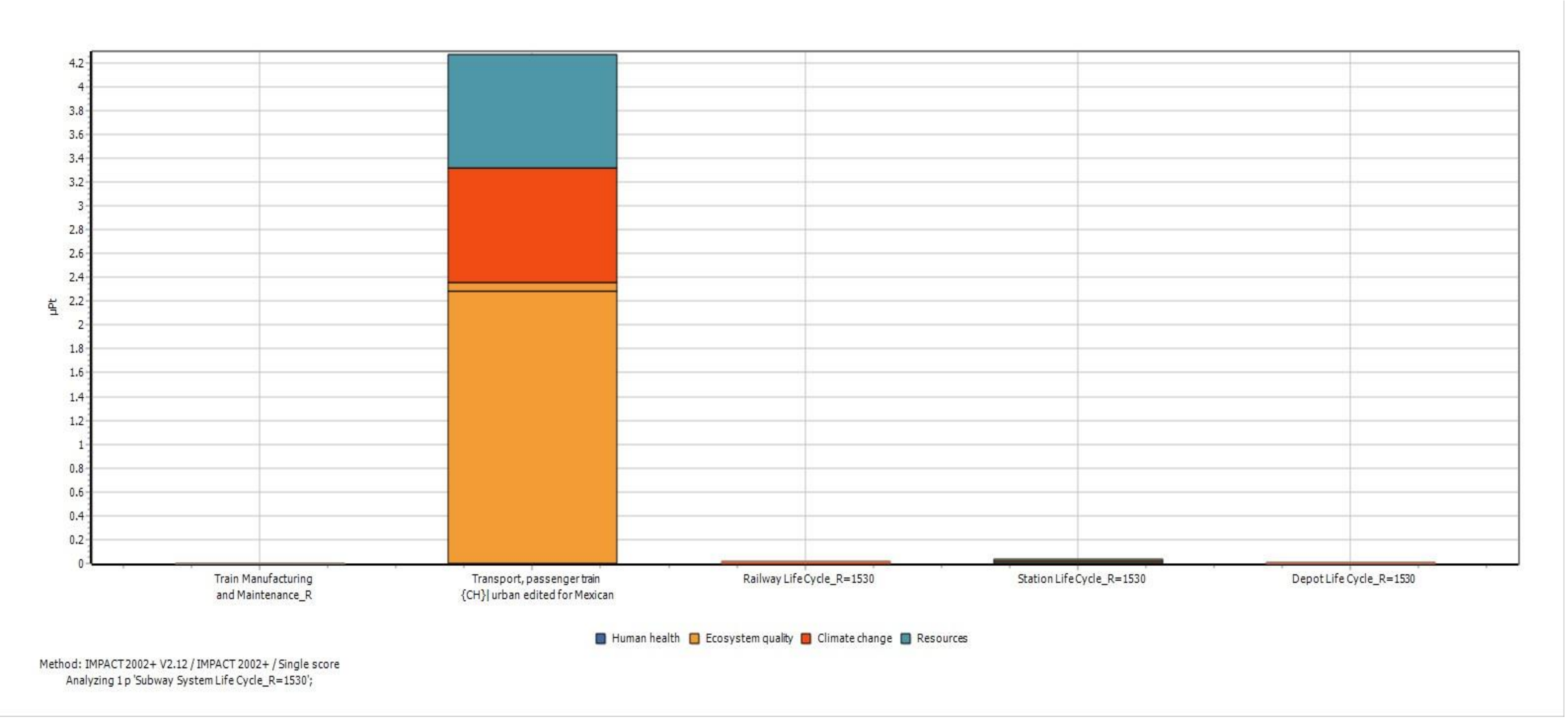


Figure 4-23. Subway, Base Case, Single Score, Impact 2002+ (Simapro software).

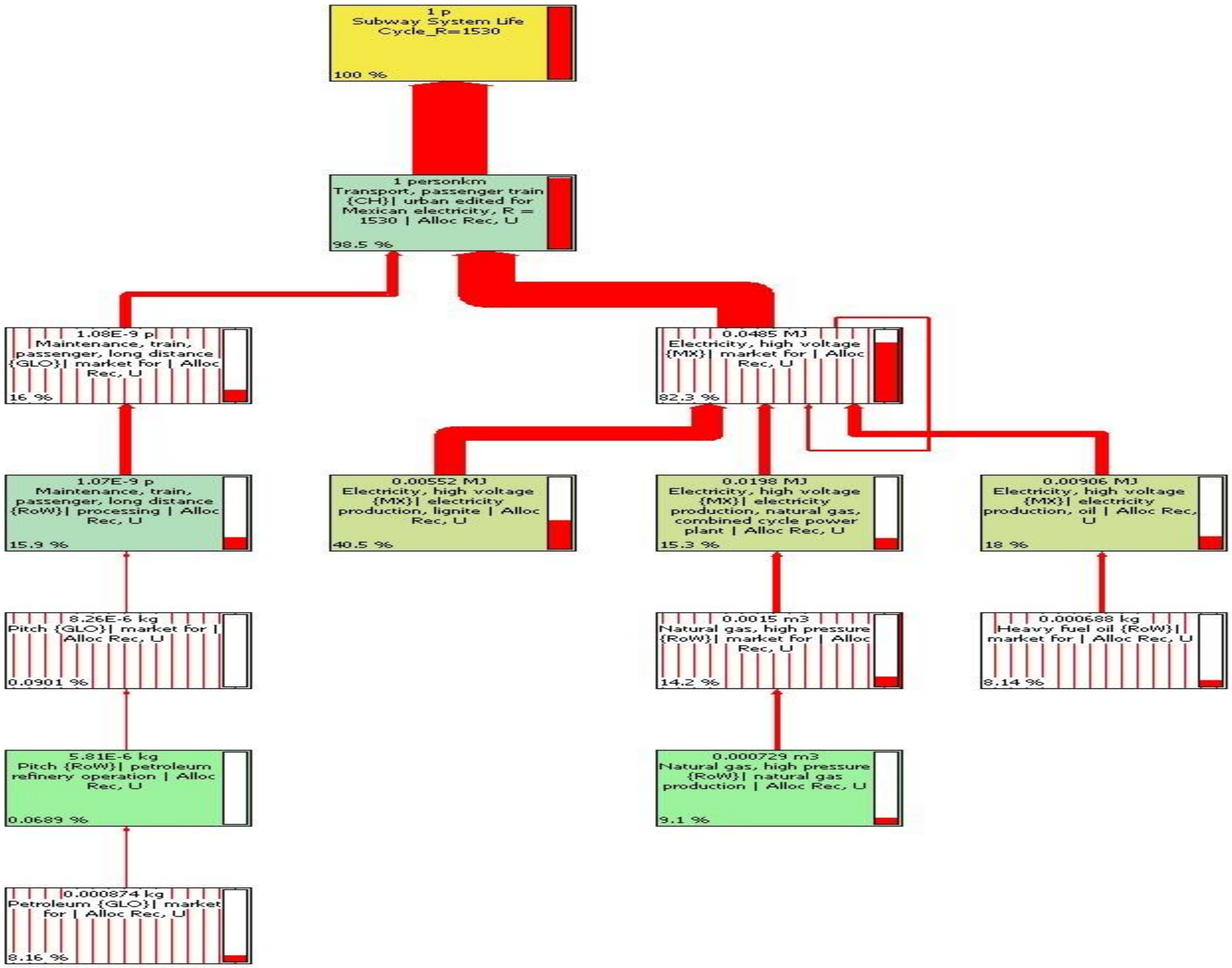


Figure 4-24. Subway, Base Case, Network Single Score, Impact 2002+ (Simapro software).

Table 4-8. Impact 2002+ Single Score Results for Subway.

Damage category	Unit	Total	Train Manuf. & Maint R=1530	Transport, pass. train urban edited Mexican electricity, R = 1530	Railway Life Cycle R=1530	Station Life Cycle R=1530	Depot Life Cycle R=1530	Vehicle Percentage	Railway Percentage	Station Percentage	Depot Percentage
Total	µPt	4.34	3.57E-13	4.27	0.01904	0.04073	0.006483	98.47%	0.44%	0.94%	0.15%
Human health	µPt	2.32	1.76E-13	2.29	0.00798	0.01950	0.003139	98.68%	0.34%	0.84%	0.14%
Ecosystem quality	µPt	0.074	3.68E-14	0.072	0.00120	0.00107	0.000167	96.72%	1.62%	1.44%	0.23%
Climate change	µPt	0.981	7.221E-14	0.959	0.00554	0.01400	0.002194	97.78%	0.57%	1.43%	0.22%
Resources	µPt	0.963	7.12E-14	0.951	0.00432	0.00616	0.000982	98.81%	0.45%	0.64%	0.10%

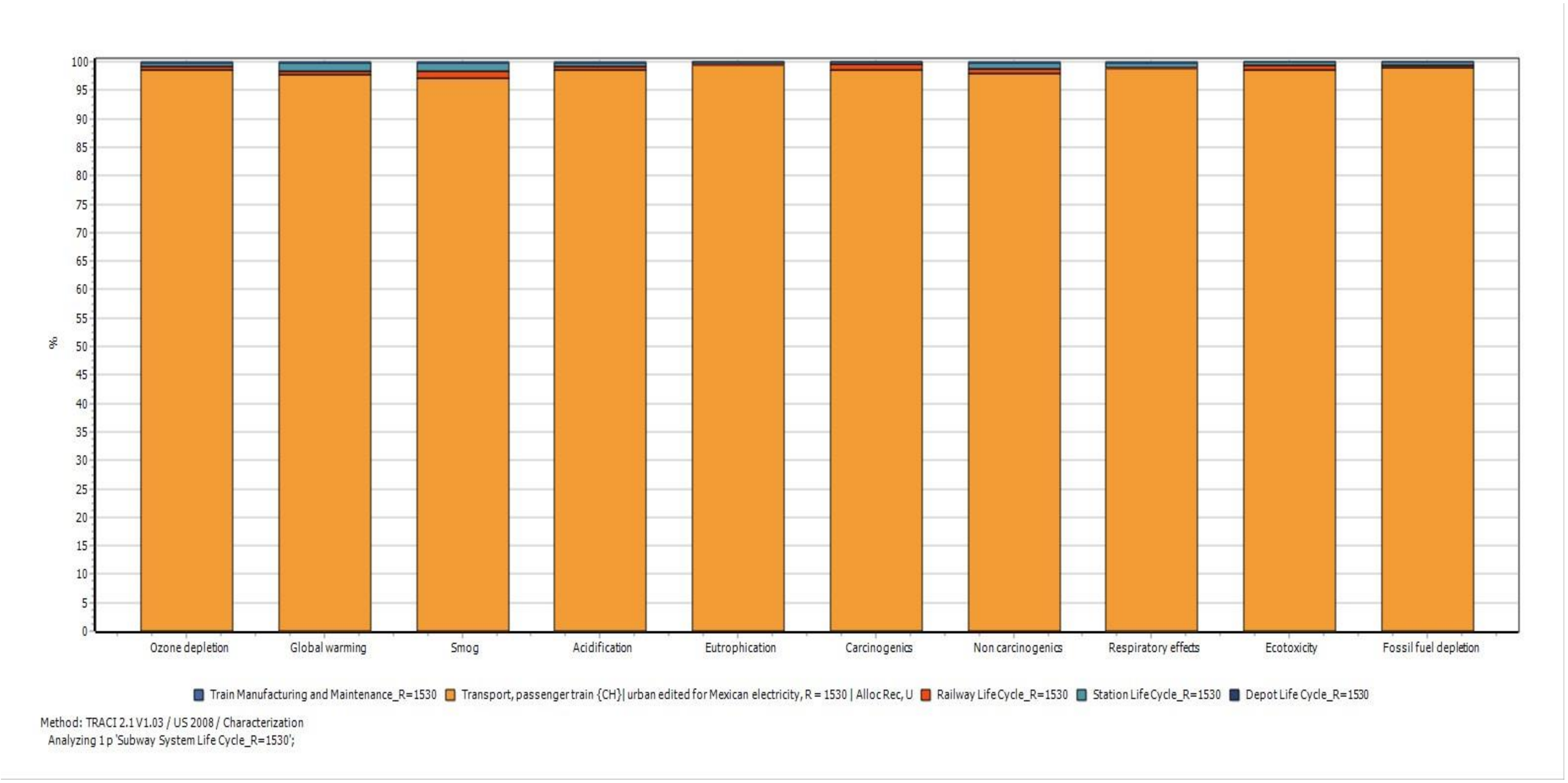


Figure 4-25. Subway, Base Case, Characterization, Traci (Simapro software).

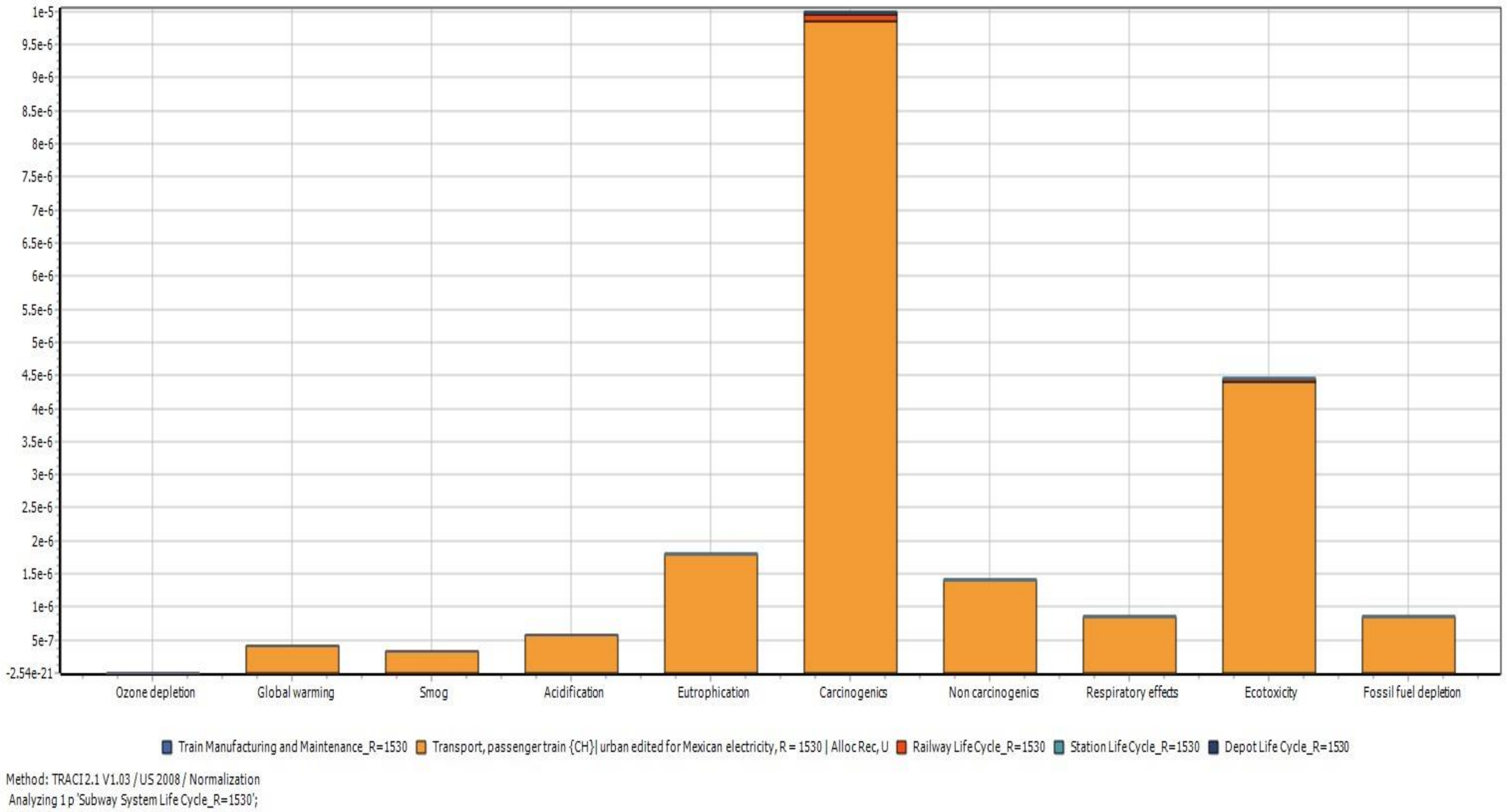


Figure 4-26. Subway, Base Case, Normalization, Traci (Simapro software).

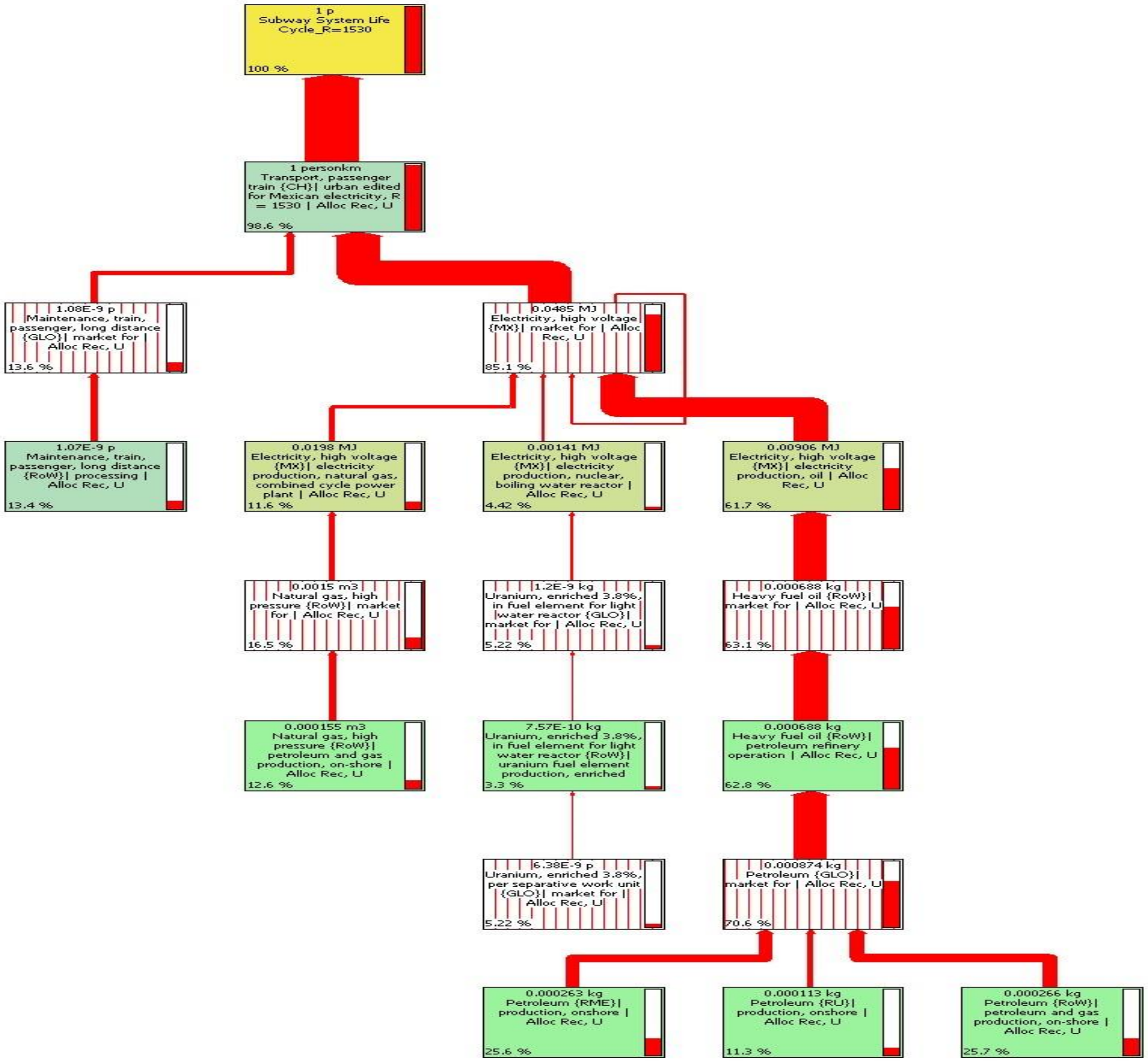


Figure 4-27. Subway, Base Case, Network Characterization, Traci (Simapro software).

4.2 Results for Research Objective 2, Part 1 (Case Study for Mexico City's BRT)

As referenced before, the method of choice for the impact assessment portion of this LCA was the BEES+ method, mainly because it is an endpoint method. Moreover, since it is one of the two North American methods (the other one being Traci), given the extensive use of North American data in this study, it was decided that BEES+ was a better fit for this LCA. BEES+ results are shown below.

4.2.1 Inventory Analysis for the BRT

Table 4-9 presents selected greenhouse gases and criteria air pollutants in the inventory resulting from the BRT's base case, along with percentage contributions of each subsystem. It is clear that the vehicle subsystem generates the vast majority of all air pollutants, but the station module also plays a significant role. Figure 4-28 presents the results of analyzing the top contributors to the Base Case's inventory with the BEES+ method, in its single score phase; this represents the top air pollutants in the inventory relative to each other.

Additionally, a life cycle inventory analysis was run on each of the individual infrastructure modules. Table 4-10 presents the inventory analysis for a single depot, while Table 4-11 presents the inventory analysis, over the life cycle, of a unit kilometer of road. As can be seen from these tables, the contribution to the airborne emissions inventory of the electricity for the infrastructure, in the operation phase, i.e., the electricity required for the illumination of each infrastructure module respectively, is substantial, reaching a high percentage of 81.27% for ozone and almost three quarters (74.91%) of the nitrous oxide (dinitrogen oxide) for the depot, and a very high 97% of the ozone present in the inventory for the unit kilometer of road.

Table 4-9. BRT, Base Case, Inventory of Airborne Pollutants: Greenhouse Gases and Criteria Air Pollutants.

Substance	Unit	Total	Vehicle BRT	Maintenance, bus {RoW}| processing | Alloc Rec, U	Depot Life Cycle	Road Life Cycle	Station Life Cycle	Vehicle Percentage	Station Percentage	Road Percentage	Depot Percentage	Maintenance Percentage
Carbon dioxide, fossil	kg	0.0154	0.0137	1.54E-06	0.00022	0.0007	8E-04	88.67%	5.39%	4.54%	1.40%	0.01%
Carbon monoxide	kg	5.29E-07	2.27E-09	0	2.6E-11	5E-07	6E-08	0.43%	10.70%	88.86%	0.00%	0.00%
Dinitrogen monoxide	kg	2.28E-07	1.10E-07	5.08E-11	1.3E-08	4E-08	6E-08	48.48%	27.77%	17.95%	5.77%	0.02%
Hydrocarbons, unspecified	kg	4.71E-06	4.71E-06	2.92E-15	3.1E-11	7E-13	3E-09	99.93%	0.07%	0.00%	0.00%	0.00%
Lead	kg	4.68E-09	2.96E-09	8.95E-13	2.7E-10	3E-10	1E-09	63.11%	24.16%	6.96%	5.76%	0.02%
Methane, fossil	kg	1.25E-05	2.59E-06	5.55E-09	1.1E-06	6E-06	3E-06	20.79%	25.30%	45.12%	8.74%	0.04%
Nitrogen dioxide	kg	6.51E-06	6.46E-06	0	3.5E-16	5E-08	5E-09	99.19%	0.08%	0.73%	0.00%	0.00%
Nitrogen oxide	kg	7.44E-05	7.44E-05	0	0	0	0	100.00%	0.00%	0.00%	0.00%	0.00%
Nitrogen oxides	kg	0.000149	0.000145	3.33E-09	4.8E-07	2E-06	2E-06	97.23%	1.24%	1.20%	0.32%	0.00%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	7.18E-06	6.47E-06	4.64E-10	8.8E-08	2E-07	4E-07	90.09%	5.49%	3.19%	1.22%	0.01%
Ozone	kg	7.59E-09	1.34E-09	8.86E-12	7.8E-10	2E-09	4E-09	17.67%	51.82%	20.10%	10.30%	0.12%
Particulates, < 10 µm	kg	4.35E-06	4.35E-06	0	7E-12	6E-14	8E-10	99.98%	0.02%	0.00%	0.00%	0.00%
Particulates, < 2.5 µm	kg	6.86E-06	4.70E-06	2.72-09	2.9E-07	5E-07	1E-06	68.54%	19.70%	7.45%	4.27%	0.04%
Sulfur dioxide	kg	1.96E-05	1.45E-05	5.95E-09	6.7E-07	2E-06	3E-06	73.82%	14.72%	8.01%	3.41%	0.03%
VOC, volatile organic compounds	kg	6.84E-06	6.84E-06	0	4.1E-11	9E-10	3E-10	99.98%	0.00%	0.01%	0.00%	0.00%

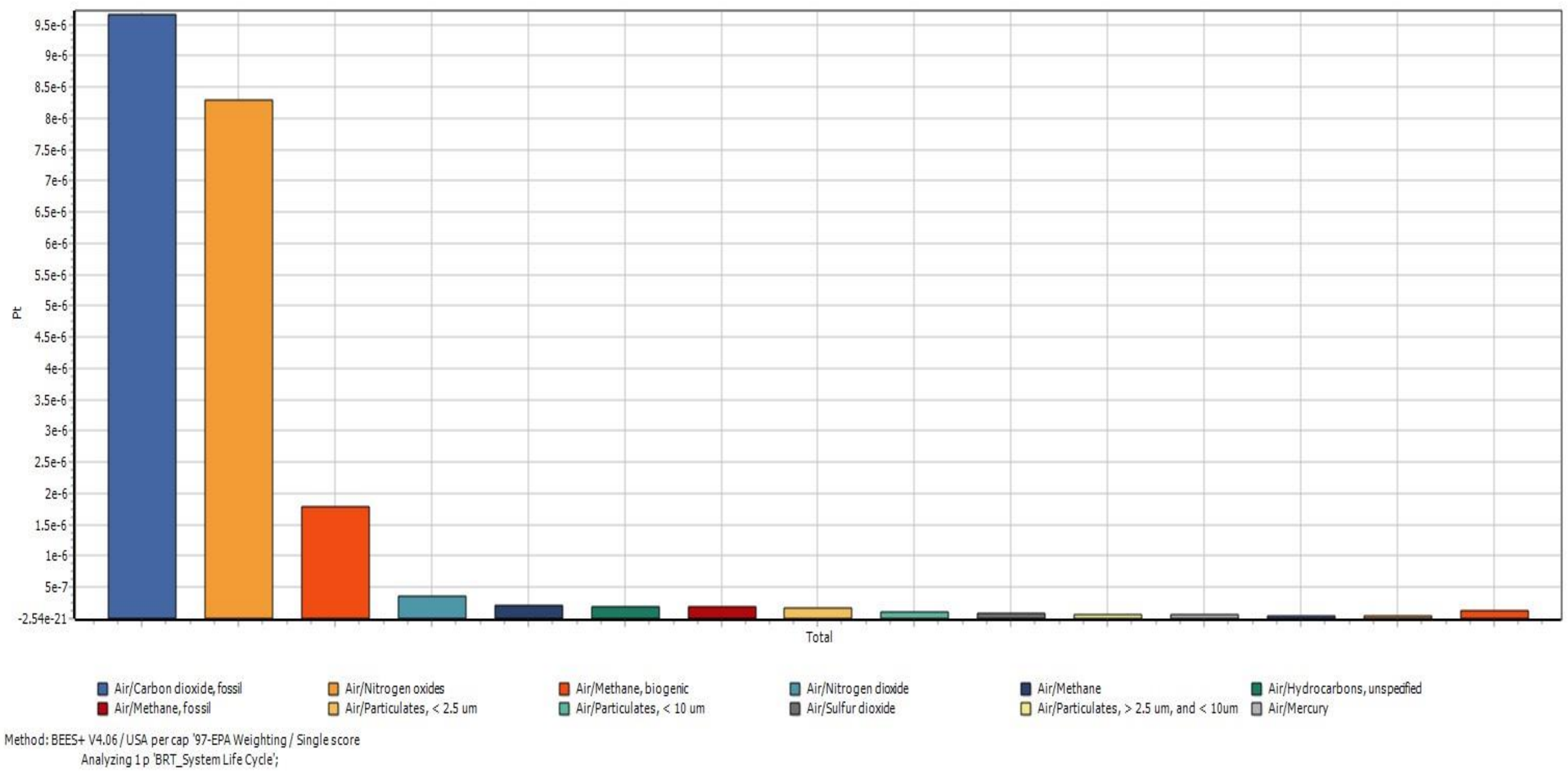


Figure 4-28. BRT, Base Case, Airborne Inventory, Single Score (Simapro software).

Table 4-10. Inventory of Greenhouse Gases and Criteria Air Pollutants for a Single Depot

Substance	Unit	Total	Depot's Construction BRT	Electricity, medium voltage {MX}| market for | Alloc Rec, U	Municipal solid waste (waste scenario) {RoW}, landfill | Alloc Rec, U	Depot Construction's Percentage	Electricity Percentage	Waste Percentage
Carbon dioxide, fossil	kg	7.20E-05	4.08E-05	2.75E-05	3.74E-06	56.63%	38.18%	5.19%
Carbon monoxide, fossil	kg	1.22E-07	1.04E-07	9.45E-09	9.32E-09	84.66%	7.72%	7.62%
Dinitrogen monoxide	kg	4.38E-09	4.28E-10	3.25E-09	7.02E-10	9.78%	74.19%	16.03%
Hydrocarbons, unspecified	kg	1.03E-11	1.03E-11	1.21E-14	6.71E-15	99.82%	0.12%	0.07%
Lead	kg	8.98E-11	8.13E-11	6.96E-12	1.53E-12	90.55%	7.74%	1.70%
Methane, fossil	kg	3.63E-07	1.70E-07	3.22E-08	1.61E-07	46.77%	8.86%	44.36%
Nitrogen dioxide	kg	1.17E-16	1.17E-16	0	0	100.00%	0.00%	0.00%
Nitrogen oxides	kg	1.61E-07	9.07E-08	5.34E-08	1.73E-08	56.21%	33.09%	10.70%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	2.92E-08	1.95E-08	7.23E-09	2.51E-09	66.69%	24.74%	8.57%
Ozone	kg	2.61E-10	3.95E-11	2.12E-10	9.29E-12	15.16%	81.27%	3.56%
Particulates, < 10 µm	kg	2.33E-12	2.33E-12	0	0	100.00%	0.00%	0.00%
Particulates, < 2.5 µm	kg	9.76E-08	4.03E-08	5.30E-08	4.28E-09	41.32%	54.29%	4.39%
Sulfur dioxide	kg	2.23E-07	9.61E-08	1.14E-07	1.31E-08	42.98%	51.14%	5.88%
VOC, volatile organic compounds	kg	1.37E-11	1.37E-11	0	0	100.00%	0.00%	0.00%

Table 4-11. Inventory of Greenhouse Gases and Criteria Air Pollutants for a Unit Kilometer of Road, BRT

Substance	Unit	Total	Road Construction _BRT	Electricity, medium voltage {MX}| market for | Alloc Rec, U	Municipal solid waste (waste scenario) {RoW} | Alloc Rec, U	Road's Construction Percentage	Electricity Percentage	Waste Percentage
Carbon dioxide, fossil	kg	0.000130	1.57E-05	0.000110	3.92E-06	12.10%	84.89%	3.01%
Carbon monoxide, fossil	kg	6.85E-08	2.07E-08	3.80E-08	9.76E-09	30.29%	55.45%	14.26%
Dinitrogen monoxide	kg	1.40E-08	1.82E-10	1.31E-08	7.44E-10	1.30%	93.37%	5.33%
Hydrocarbons, unspecified	kg	6.97E-14	1.40E-14	4.86E-14	7.05E-15	20.16%	69.72%	10.12%
Lead	kg	3.79E-11	8.32E-12	2.79E-11	1.61E-12	21.97%	73.78%	4.26%
Methane	kg	8.16E-10	8.16E-10	1.23E-14	1.83E-15	100.00%	0.00%	0.00%
Nitrogen dioxide	kg	1.58E-09	1.58E-09	0	0	100.00%	0.00%	0.00%
Nitrogen oxides	kg	2.67E-07	3.44E-08	2.15E-07	1.81E-08	12.89%	80.32%	6.79%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.57E-08	4.04E-09	2.90E-08	2.62E-09	11.32%	81.33%	7.35%
Ozone	kg	8.73E-10	1.27E-11	8.51E-10	9.83E-12	1.45%	97.42%	1.13%
Particulates, < 10 µm	kg	2.06E-15	2.06E-15	0	0	100.00%	0.00%	0.00%
Particulates, < 2.5 µm	kg	2.23E-07	5.42E-09	2.13E-07	4.52E-09	2.43%	95.54%	2.03%
Sulfur dioxide	kg	4.96E-07	2.33E-08	4.59E-07	1.39E-08	4.69%	92.51%	2.80%
VOC, volatile organic compounds	kg	2.90E-11	2.90E-11	0	0	100.00%	0.00%	0.00%

4.2.2 Impact Assessment for the BRT

Figure 4-29 to Figure 4-32 show the characterization, normalization, weighting and single score phases, respectively, of the BEES+ method applied to the Base Case of the BRT system. Figure 4-33 presents the Network diagram for the single score phase of the BEES+ method, when applied to the full BRT system. The vehicle's subsystem accounts for 65% of the score, the depot for 2.8%, the station for 9.73% and the road module for 22.4%. This marks a difference in the percentages assigned to each subsystem or module relative to what was assigned to them by the Impact 2002+ (85% for the vehicle by Impact 2002+).

Additionally, an impact assessment was conducted on each of the infrastructure modules' construction separately. Figure 4-34 shows the results of this analysis for the construction of a single station, Figure 4-35 shows the corresponding results for a unit kilometer of hydraulic concrete as road for the BRT, and finally, Figure 4-36 shows the results of the construction of a depot. As can be observed in these figures, the construction elements with the greatest impacts throughout the life cycle are the structural steel and cement for the station and the depot, and the cement for the hydraulic concrete of the road, with the rest of the construction materials quickly falling behind in impact. Nevertheless, it is also interesting to note that the "natural stone" for the station, representing the walls' granite coverings, also had a significant impact, as did the polycarbonate sheets employed in the roofing of both the station and depot.

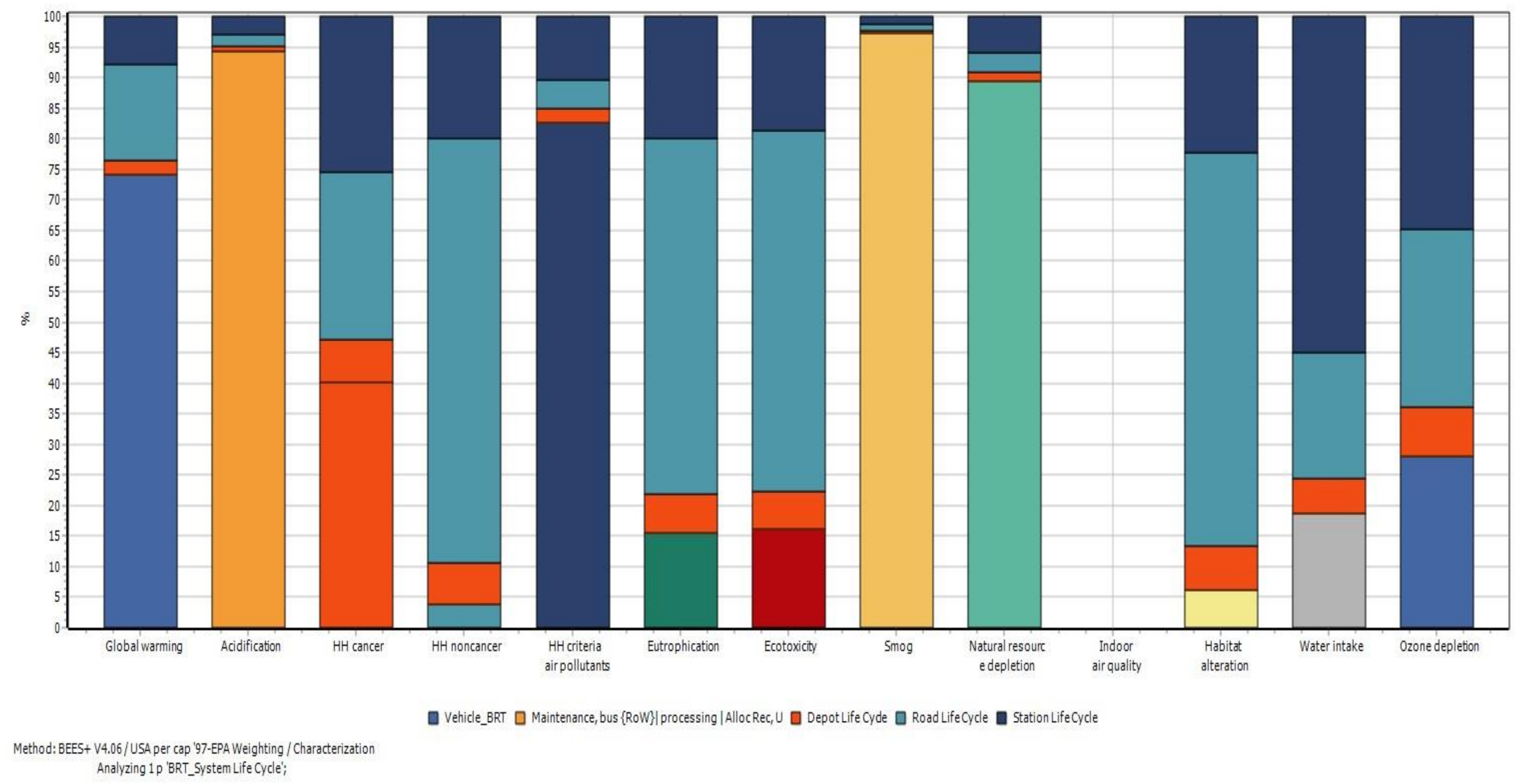


Figure 4-29. BRT, Base Case, Characterization, BEES+. (Simapro software).

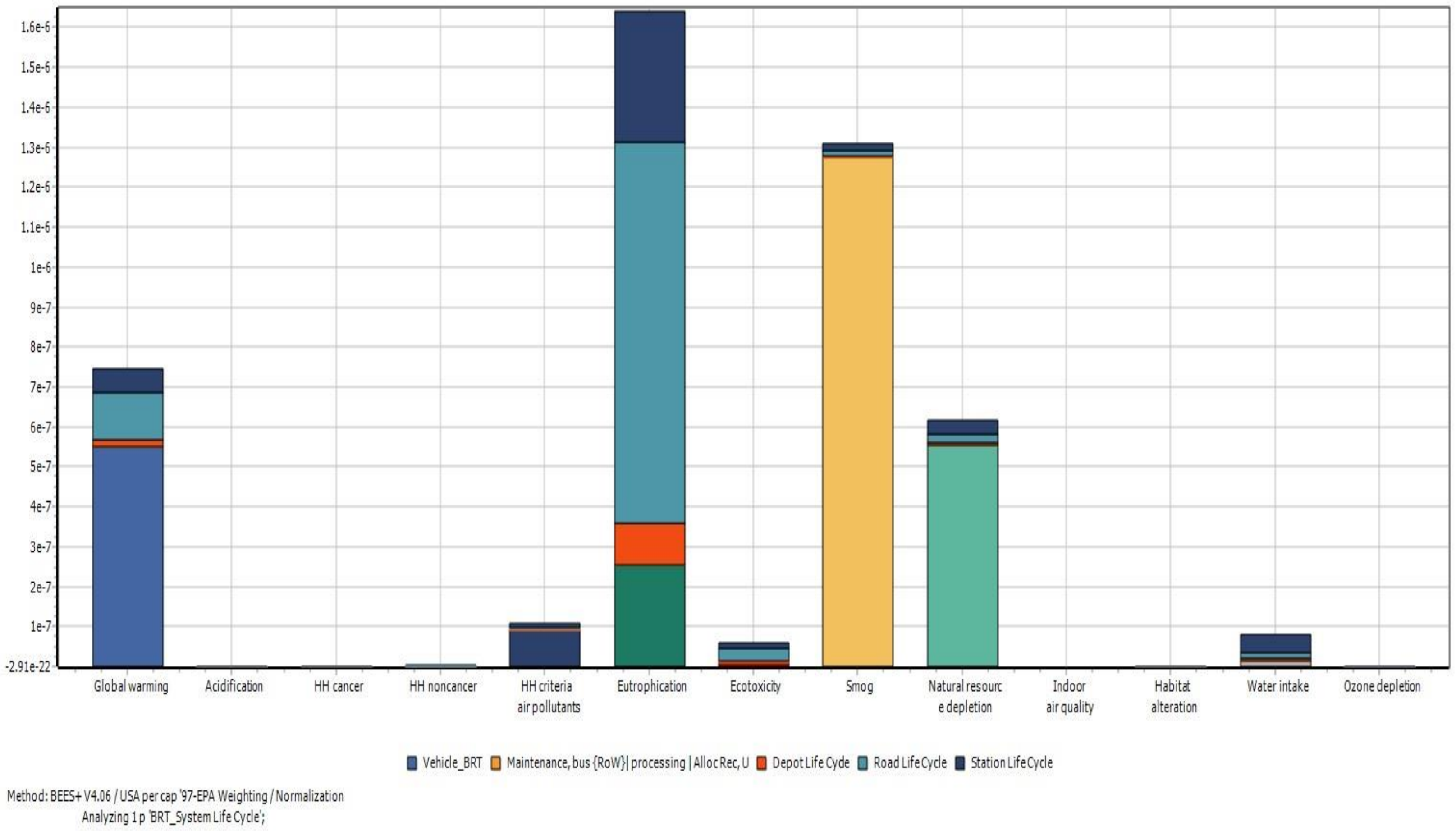


Figure 4-30. BRT, Base Case, Normalization, BEES+. (Simapro software).

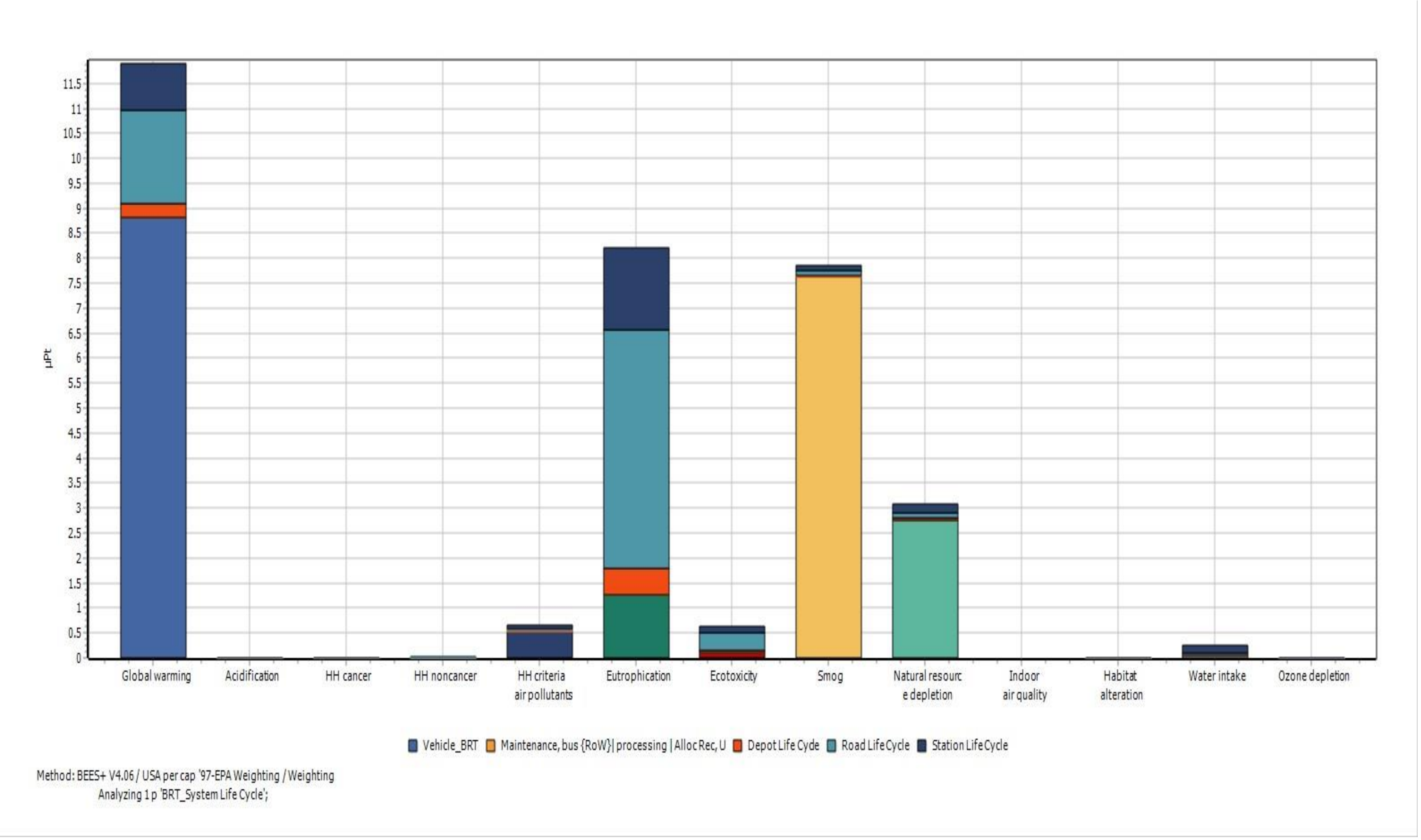


Figure 4-31. BRT, Base Case, Weighting, BEES+. (Simapro software).

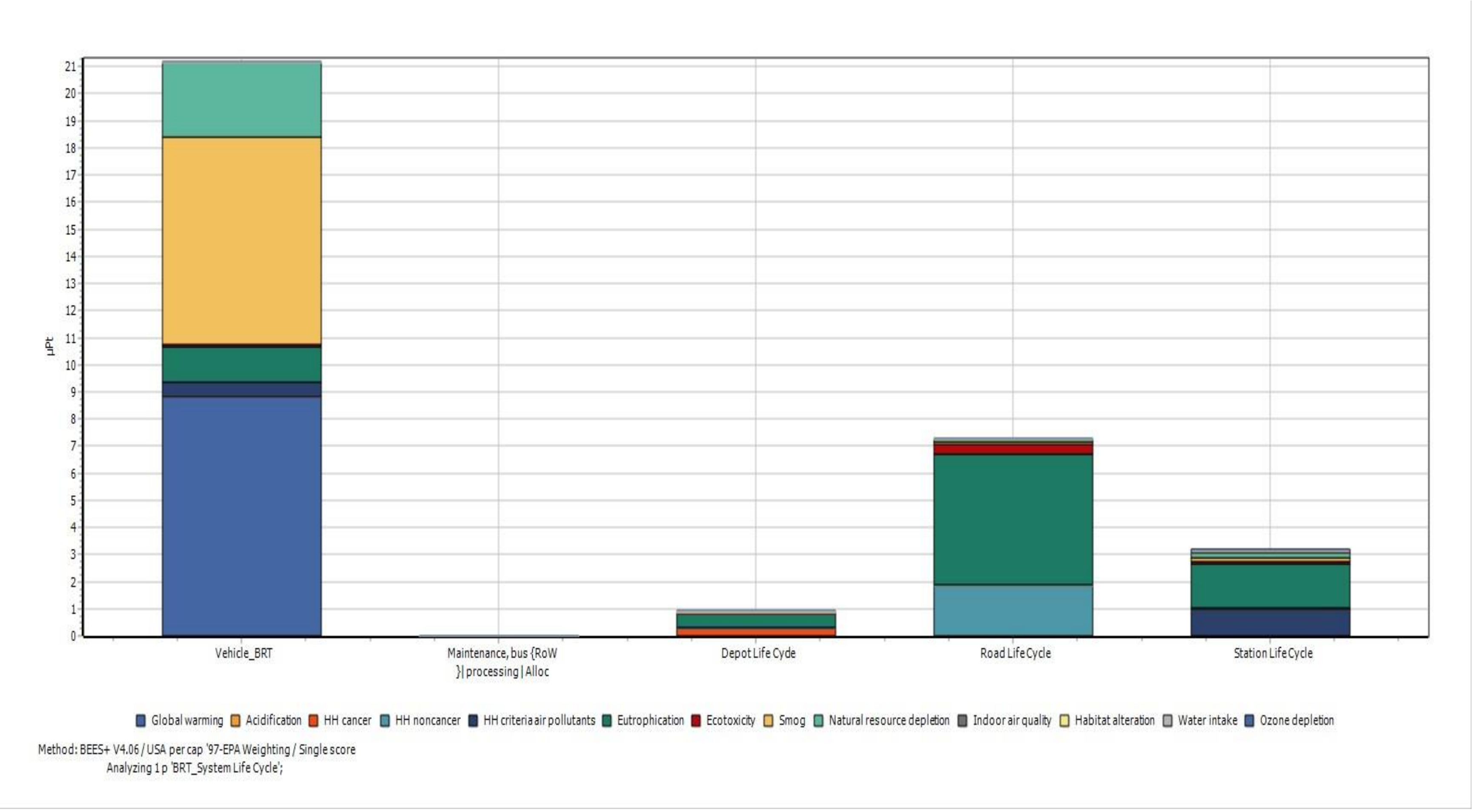


Figure 4-32. BRT, Base Case, Single Score, BEES+. (Simapro software).

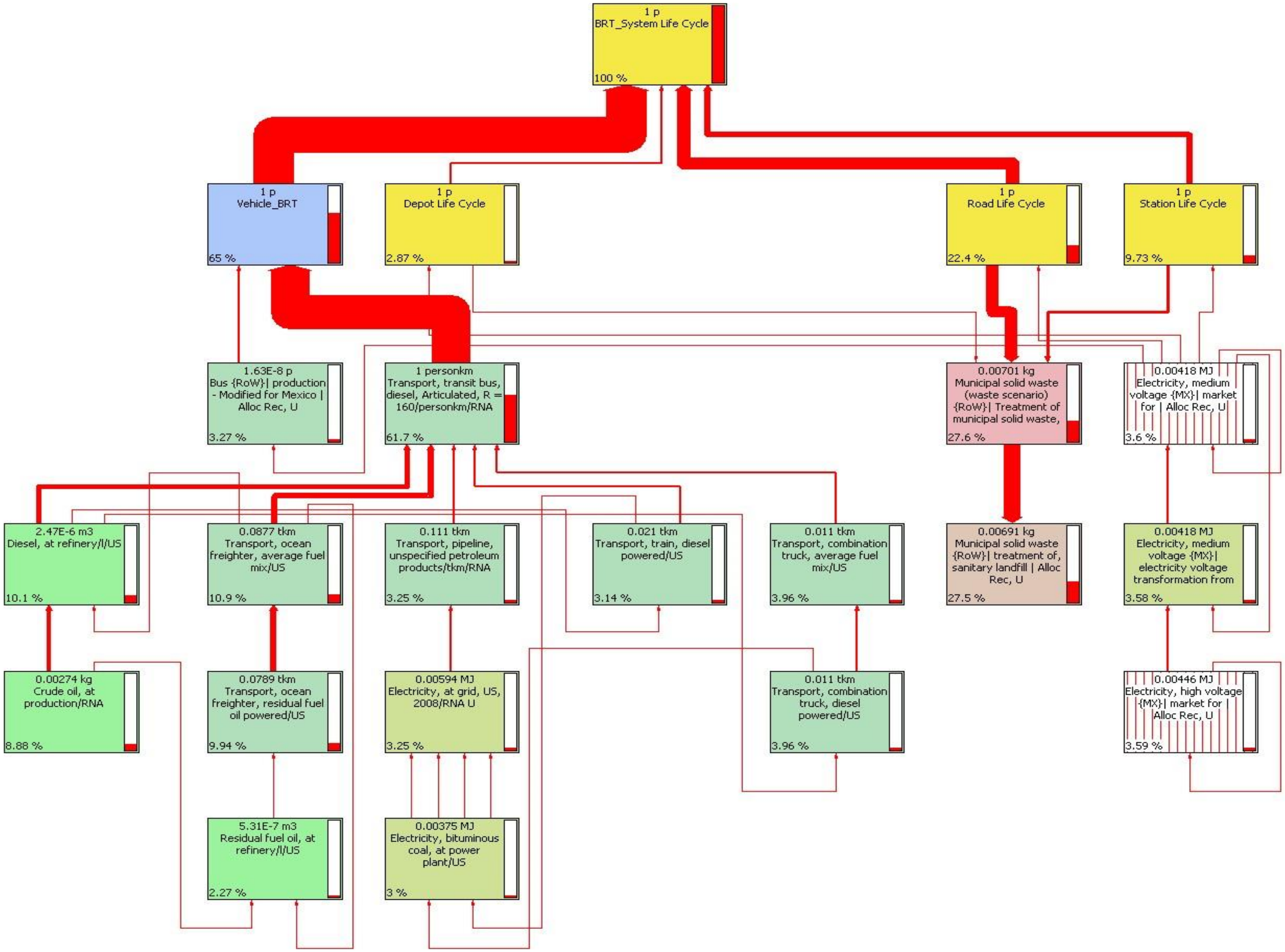


Figure 4-33. BRT, Base Case, Network Single Score, at cut-off 5%, BEES+. (Simapro software)

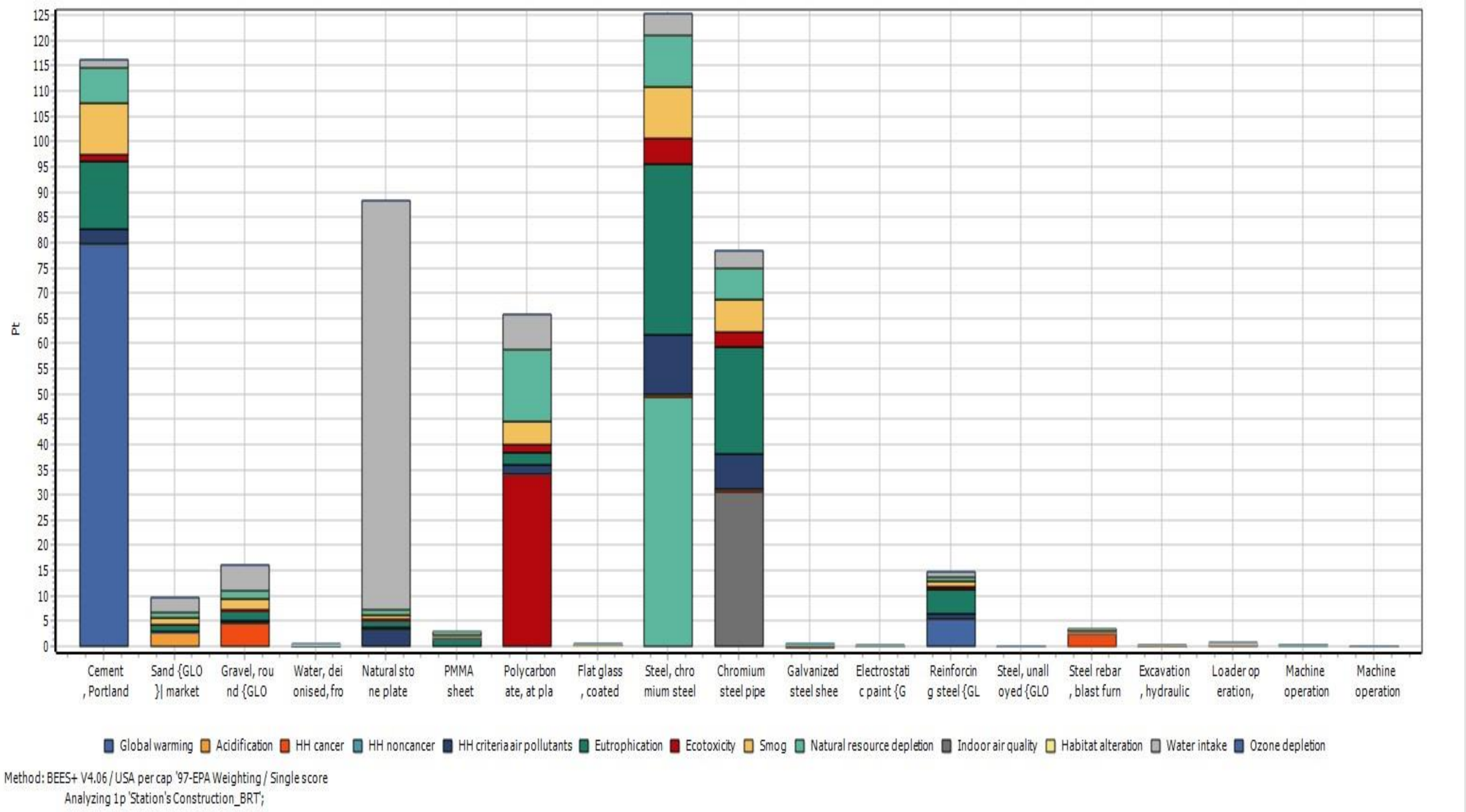


Figure 4-34. Impact Assessment of the Construction of a Station for the BRT, Single Score, BEES+. (Simapro Software).

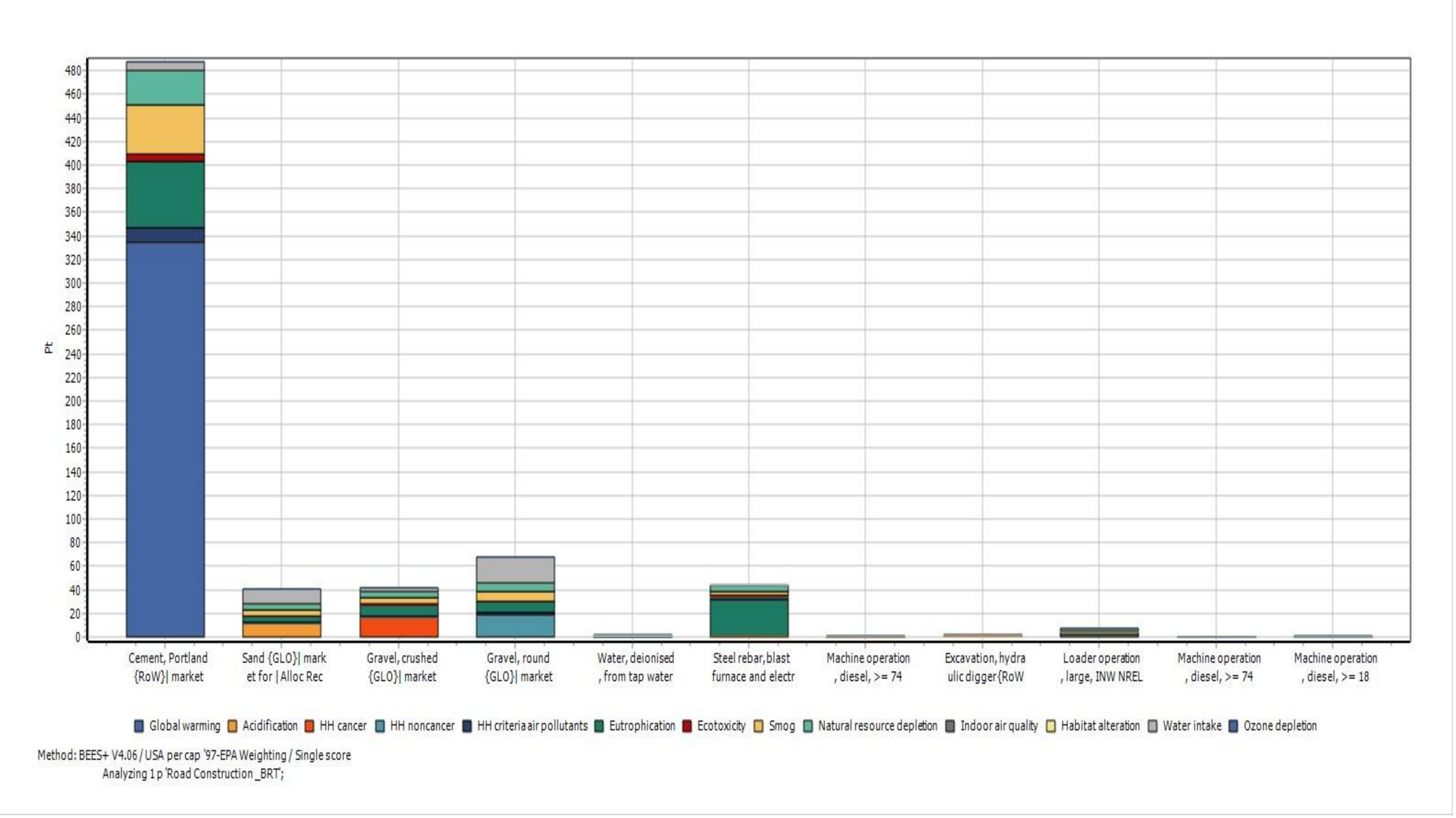
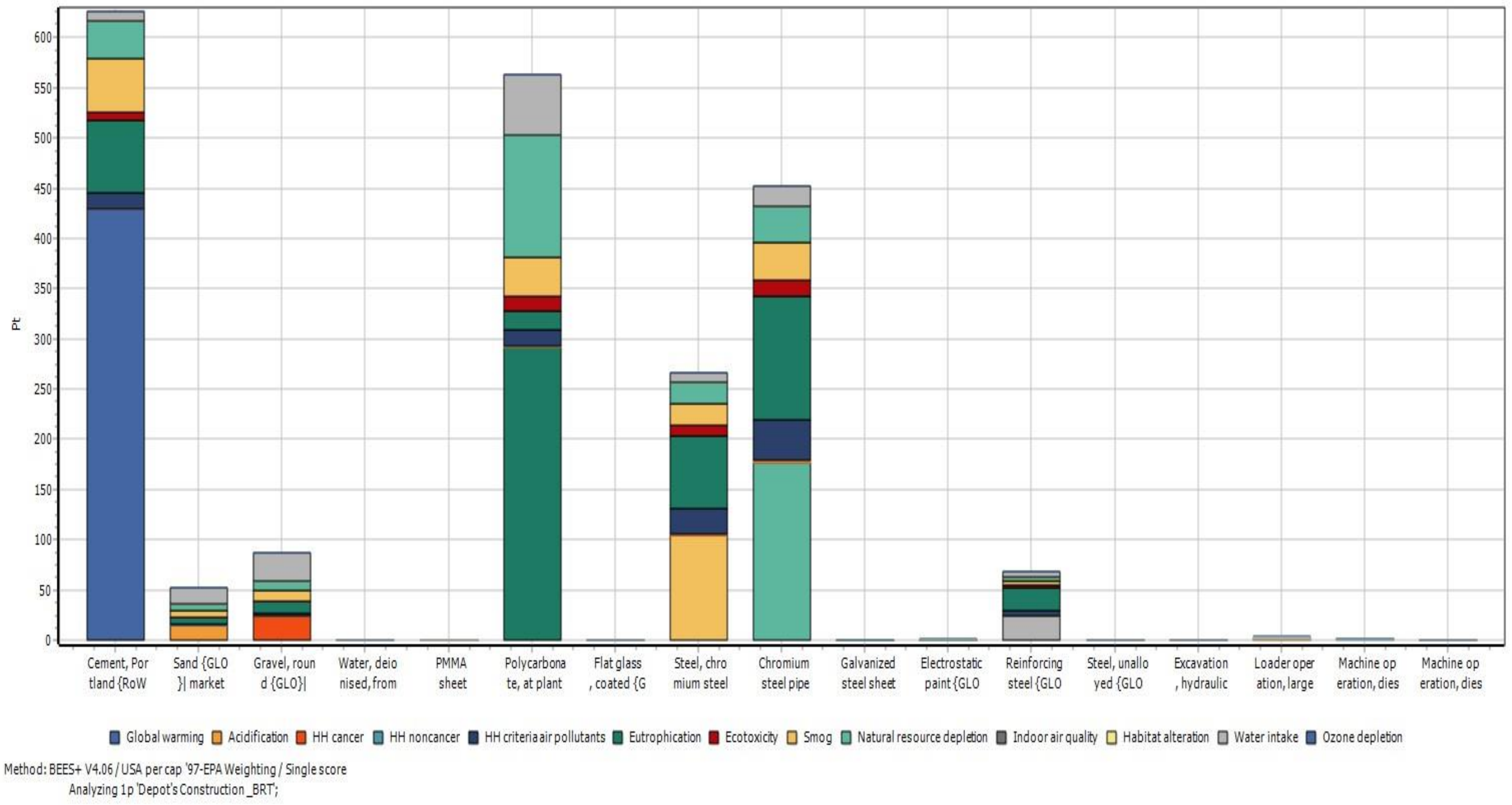


Figure 4-35. Impact Assessment of the Construction of a Unit Kilometer of Road for the BRT, Single Score, BEES+. (Simapro Software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Single score
Analyzing 1 p 'Depot's Construction _BRT';

Figure 4-36. Impact Assessment of the Construction of a Depot for the BRT, Single Score, BEES+. (Simapro Software).

4.3 Results for Research Objective 2, Part 2 (Case Study for Mexico City, Private Car)

As mentioned above, the chosen method for this LCA was the BEES+ method, mainly because it is the only endpoint for North America included in Simapro.

4.3.1 Inventory Analysis for the Car

Although some preliminary inventory results were presented in Section 4.1.2, Table 4-12 presents the Criteria Air Pollutants (CAP) and GHG gases in the inventory of the car's base case, along with the percentages of each subsystem or module to the total. The dominance of the road's life cycle in the total amount of $PM_{2.5}$ is observed once again. Further, it can be seen that the road also has a very significant contribution in ozone emissions, with 66.97% of the total. As far as the vehicle maintenance and manufacturing is concerned, lead is contributed in almost its totality by this module, with 91.57%; this is naturally due to the lead in the car's battery. Regarding the vehicle's subsystem, it contributes 100% of the nitrogen oxides, as expected, and with the vast majority of almost all GHG: carbon dioxide and nitrous oxide (dinitrogen monoxide) with 74.14% and 57.31%, respectively. However, methane is contributed in a much larger share by the vehicle manufacturing and maintenance, 72.12%, probably due to the use of cleaning fluids for maintenance, and to the wear and tear of different auto parts.

Additionally, a life cycle inventory analysis was made on a unit kilometer of road built for the car, in this case, of flexible pavement, or asphaltic pavement. This inventory is presented in Table 4-13, in abbreviated form, and with the contribution percentages calculated for the two top generators of air pollutants: the bitumen (asphalt) of the flexible pavement and the electricity used during the system's lifespan, specifically for the illumination of the road. This table shows that while the electricity used for lighting of the road, in a single unit or a one-time occurrence would probably have a negligible effect, it is precisely its continuous usage, for approximately 10 to 12 hours per day, depending on the season, throughout the life cycle, which accounts for its very significant effect. Electricity by itself accounts for the almost totality of the ozone generated in the lifecycle of a unit kilometer of the road (99.04%), of $PM_{2.5}$ (98.34%), of N_2O (98.53%), with very high percentages also for lead (86.31%), and for sulfur dioxide (87.99%). On the other hand, bitumen is almost totally responsible for the generation of unspecified hydrocarbons (99.41%), of methane (99.91%) and of VOCs (98.56%), which is probably due both to the laying of the asphalt, with its great demand of heat, and to the chemical composition of the tar substrate, high in hydrocarbons and methane. Hence, most of the air pollution resulting from the flexible pavement, under the considerations for this life cycle, can be attributed, at the inventory level, just to these two reference flows.

Table 4-12. Car, Base Case, Inventory of Airborne Pollutants: Greenhouse Gases and Criteria Air Pollutants.

Substance	Unit	Total	Vehicle Manufacturing and Maintenance	Transport, passenger car, gasoline, R = 1.7 /personkm/RNA	Road Life Cycle - R1.7	Manufact. & Maint. Percentage	Vehicle Operation Percentage	Road Percentage
Carbon dioxide, fossil	kg	0.221	0.0291	0.164	0.0280	13.19%	74.14%	12.68%
Carbon monoxide, fossil	kg	0.00334	0.000171	0.00306	0.000105	5.14%	91.73%	3.14%
Dinitrogen monoxide	kg	9.32E-06	1.04E-06	5.34E-06	2.93E-06	11.21%	57.31%	31.48%
Hydrocarbons, unspecified	kg	0.000202	1.72E-10	0.000202	2.72E-09	0.00%	100.00%	0.00%
Lead	kg	9.6E-08	8.79E-08	9.21E-10	7.17E-09	91.57%	0.96%	7.47%
Methane, fossil	kg	0.000146	0.000106	8.72E-06	3.14E-05	72.62%	5.96%	21.42%
Nitrogen dioxide	kg	2.99E-05	8.00E-13	0.0000299	2.47E-14	0.00%	100.00%	0.00%
Nitrogen oxides	kg	0.000676	6.96E-05	0.000533	7.26E-05	10.31%	78.95%	10.75%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	0.000184	5.97E-05	0.000103	2.09E-05	32.44%	56.22%	11.33%
Ozone	kg	2.84E-07	9.38E-08	0	1.90E-07	33.03%	0.00%	66.97%
Particulates, < 10 µm	kg	1.20E-05	2.63E-11	1.20E-05	8.12E-13	0.00%	100.00%	0.00%
Particulates, < 2.5 µm	kg	9.22E-05	3.76E-05	6.67E-06	4.79E-05	40.80%	7.23%	51.97%
Sulfur dioxide	kg	0.000344	0.000126	0.000102	0.000116	36.82%	29.55%	33.63%
VOC, volatile organic compounds	kg	0.000217	2.34E-09	0.000216	7.96E-07	0.00%	99.63%	0.37%

Table 4-13. Inventory of Greenhouse Gases and Criteria Air Pollutants for Unit Kilometer of Road, Car.

Substance	Unit	Total	Gravel, round {GLO}| market for | Alloc Rec, U	Cement, Portland {RoW}| market for | Alloc Rec, U	Gravel, crushed {GLO}| market for | Alloc Rec, U	Bitumen, at refinery/kg/US	Water, deionized {GLO}| market for | Alloc Rec, U	Excavation, hydraulic digger {RoW} | Alloc Rec, U	Loader operation, large, NREL/RNA U	Electricity, medium voltage {MX}| Alloc Rec, U	Bitumen Percentage	Electricity Percentage
Carbon dioxide, fossil	kg	0.000560	4.45E-06	2.49E-06	6.94E-06	5.11E-05	1.88E-09	1.21E-09	4.90E-07	0.000489	9.12%	87.39%
Carbon monoxide, fossil	kg	2.094E-06	2.22E-08	1.91E-09	3.56E-08	1.84E-06	3.40E-12	4.80E-12	4.23E-09	1.68E-07	88.12%	8.03%
Dinitrogen monoxide	kg	5.87E-08	1.27E-10	1.31E-11	2.05E-10	3.49E-10	6.33E-14	4.15E-14	1.01E-12	5.78E-08	0.60%	98.53%
Hydrocarbons, unspecified	kg	5.43E-11	2.13E-14	9.89E-16	2.86E-14	5.40E-11	5.47E-18	5.77E-19	0	2.15E-13	99.49%	0.40%
Lead	kg	1.44E-10	5.64E-12	6.03E-13	8.02E-12	2.08E-12	1.69E-15	2.62E-16	1.41E-14	1.24E-10	1.45%	86.31%
Methane	kg	5.83E-07	9.47E-15	9.62E-16	3.18E-14	5.82E-07	3.36E-18	4.21E-19	5.29E-10	5.43E-14	99.91%	0.00%
Nitrogen dioxide	kg	4.93E-16	0	0	0	0	0	0	4.93E-16	0	0.00%	0.00%
Nitrogen oxides	kg	1.45E-06	2.64E-08	4.06E-09	3.26E-08	4.03E-07	4.47E-12	1.41E-11	8.86E-09	9.50-07	27.72%	65.42%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	4.17E-07	4.08E-09	3.66E-10	4.86E-09	2.74E-07	5.54E-13	2.07E-12	1.39E-09	1.29E-07	65.65%	30.84%
Ozone	kg	3.80E-09	8.43E-12	1.50E-12	2.14E-11	0	1.18E-14	4.63E-16	1.36E-13	3.77E-09	0.00%	99.04%
Particulates, < 10 µm	kg	1.62E-14	0	0	0	0	0	0	1.62E-14	0	0.00%	0.00%
Particulates, < 2.5 µm	kg	9.58E-07	4.10E-09	6.25E-10	8.22E-09	0	3.13E-12	1.43E-12	2.11E-12	9.42E-07	0.00%	98.34%
Sulfur dioxide	kg	2.31E-06	1.32E-08	2.66E-09	2.23E-08	2.29E-07	7.12E-12	1.88E-12	9.87E-11	2.03E-06	9.91%	87.99%
VOC, volatile organic compounds	kg	1.59E-08	0	0	0	1.57E-08	0	0	2.29E-10	0	98.56%	0.00%

4.3.2 Impact Assessment for the Car

With BEES+ as the EIA method chosen, the car system as a whole, comprising the vehicle, energy and infrastructure subsystems (in this case, including only the road module), was analyzed. Figure 4-37 shows the results of the characterization phase. In concordance with the inventory analysis above, it can be seen that the greatest contributors in the ozone depletion category are the road life cycle and the vehicle's manufacturing and maintenance. Further, the latter also has a very significant impact in the Human Health non-cancer category, most probably related to the engine, transmission, brake and wiper fluids mentioned above, and probably also related to the tires' synthetic rubber.

Figure 4-38 to Figure 4-40 present the normalization, weighting and single score phases of the BEES+ method applied to the car system, base case (i.e., with a ridership of 1.7 passengers, an age of 15 years, and an expected lifetime VKT of 187,500 km.). As can be observed in these figures, although the vehicle operation is the greatest generator of impacts in almost all categories, vehicle manufacturing and maintenance do show an important contribution to the eutrophication, ozone depletion and climate change categories, and the road life cycle contributes in a noticeable way in almost all categories, leading in the ozone depletion and eutrophication categories. In Figure 4-40 the contribution of each module or subsystem is represented graphically, with the vehicle manufacturing and maintenance product stage in Simapro representing 20.3% of the single score; the road 17% and the "Transport" or vehicle and energy subsystems accounting for 62.7% of the environmental impact, according to the BEES+ method. Vehicle operation ("Transport") is the leader in the smog and natural resource depletion categories, as expected. Figure 4-41 shows the network diagram for the single score assessment of the car's base case. In this figure it can be seen that the vehicle's life cycle, or "transport" accounts for 62.7% of the system's impact; the road for 17% and the vehicle's manufacturing and maintenance for 20.3% of the road. In fact, if the vehicle's "transport" contribution were added to its lifetime maintenance and manufacturing, the total contribution of the vehicle's life cycle would be 83%, leaving only 17% for the road by itself. This percentage contribution for the road or infrastructure subsystem is again in line with the percentages found by other studies (Chester, 2012), which suggest a contribution around 15-18% for the infrastructure "component".

It is noteworthy that while all EIA methods (Impact 2002+, Traci and BEES+) agree on the vehicle operation being the largest emission generator, there is divergence among the three methods as to which subsystem or module should be second greatest contributor. As mentioned in Section 4.1.2, Impact 2002+, in its single score, assigns the second place to the road life cycle, as does Traci, but the BEES+ method gives a slightly higher value to the vehicle manufacturing than to the road, as explained in the previous paragraph.

Moreover, in order to better comprehend how much of the impact of the vehicle's manufacturing and maintenance was due to manufacturing or car production, and how much to maintenance activities, an additional BEES+ method was run exclusively on this product stage.

Figure 4-42 shows the single score of the BEES+ method applied solely on the vehicle manufacturing and maintenance. It becomes clear that the greatest impact is the production of the car. Since this record within Simapro's Ecoinvent database had been selected and edited for a Mexican car (substituting for Mexican electricity and scaling it up by weight), it was further reviewed. It was discovered that this record claims to include the eventual manual dismantling of the car. Hence, the "production" is not only such, but includes the end-of-life, which explains its preponderance vis-à-vis the maintenance.

To better understand the impacts occurring during the maintenance activities, an additional EIA with the BEES+ method was run on Vehicle Maintenance product stage within Simapro. Figure 4-43 shows the results of the single score phase of this assessment. Here it can be seen that the high impact in the eutrophication category is indeed due to the car’s fluids, and that it is the synthetic rubber the one that has an important impact in the Human Health, non-cancer category.

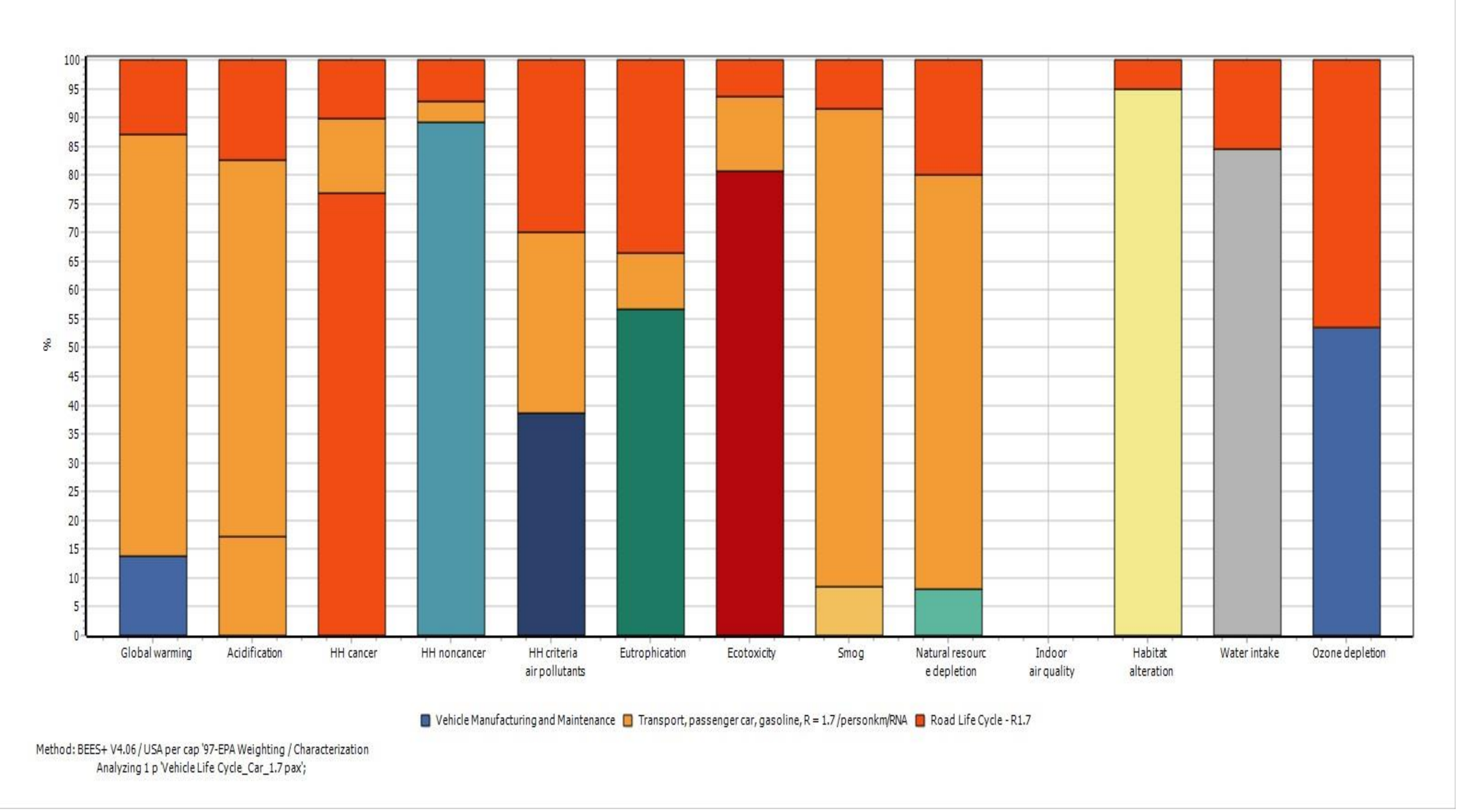


Figure 4-37. Car, Base Case, Characterization, BEES+ (Simapro software).

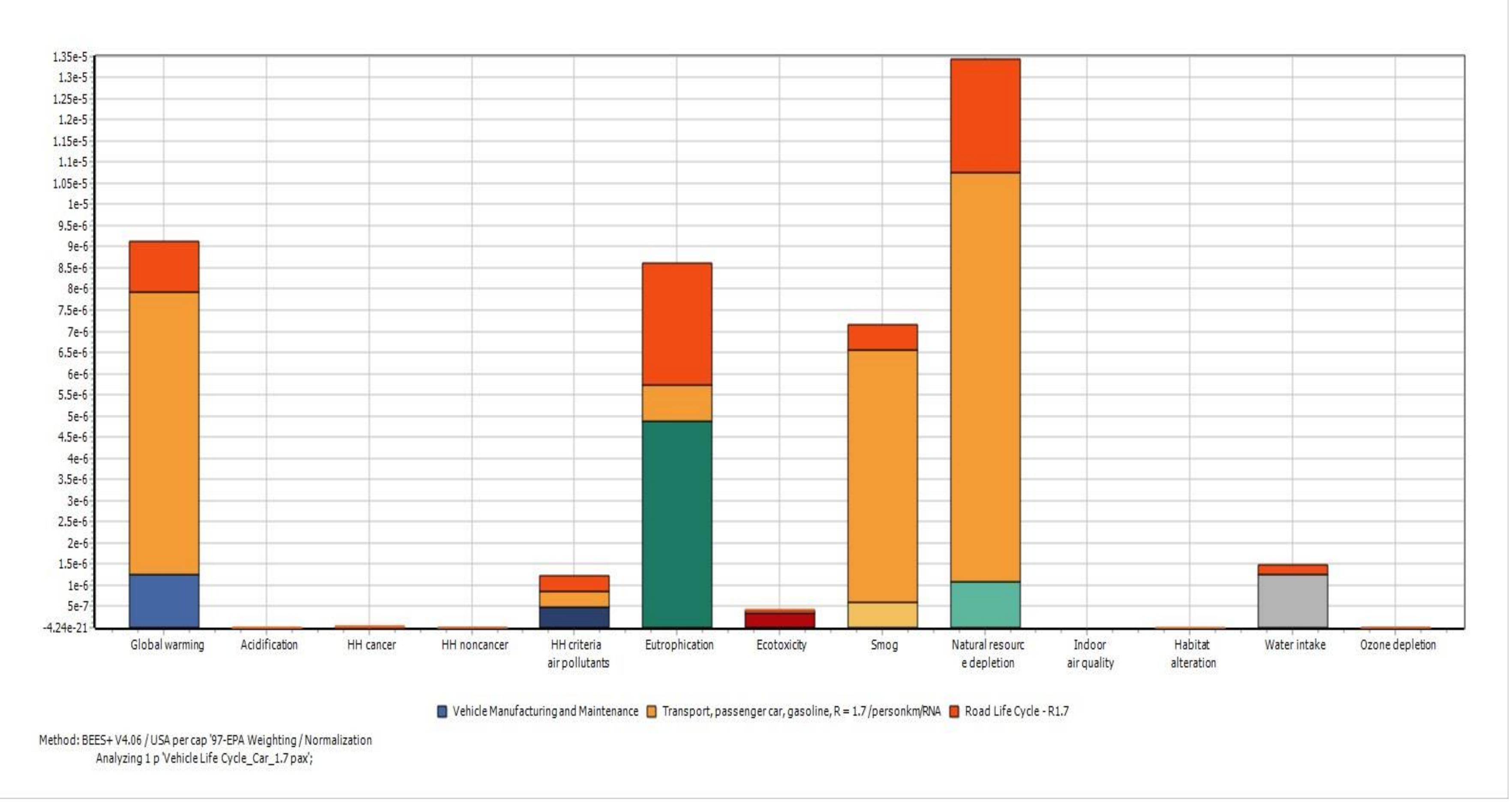


Figure 4-38. Car, Base Case, Normalization, BEES+ (Simapro software)

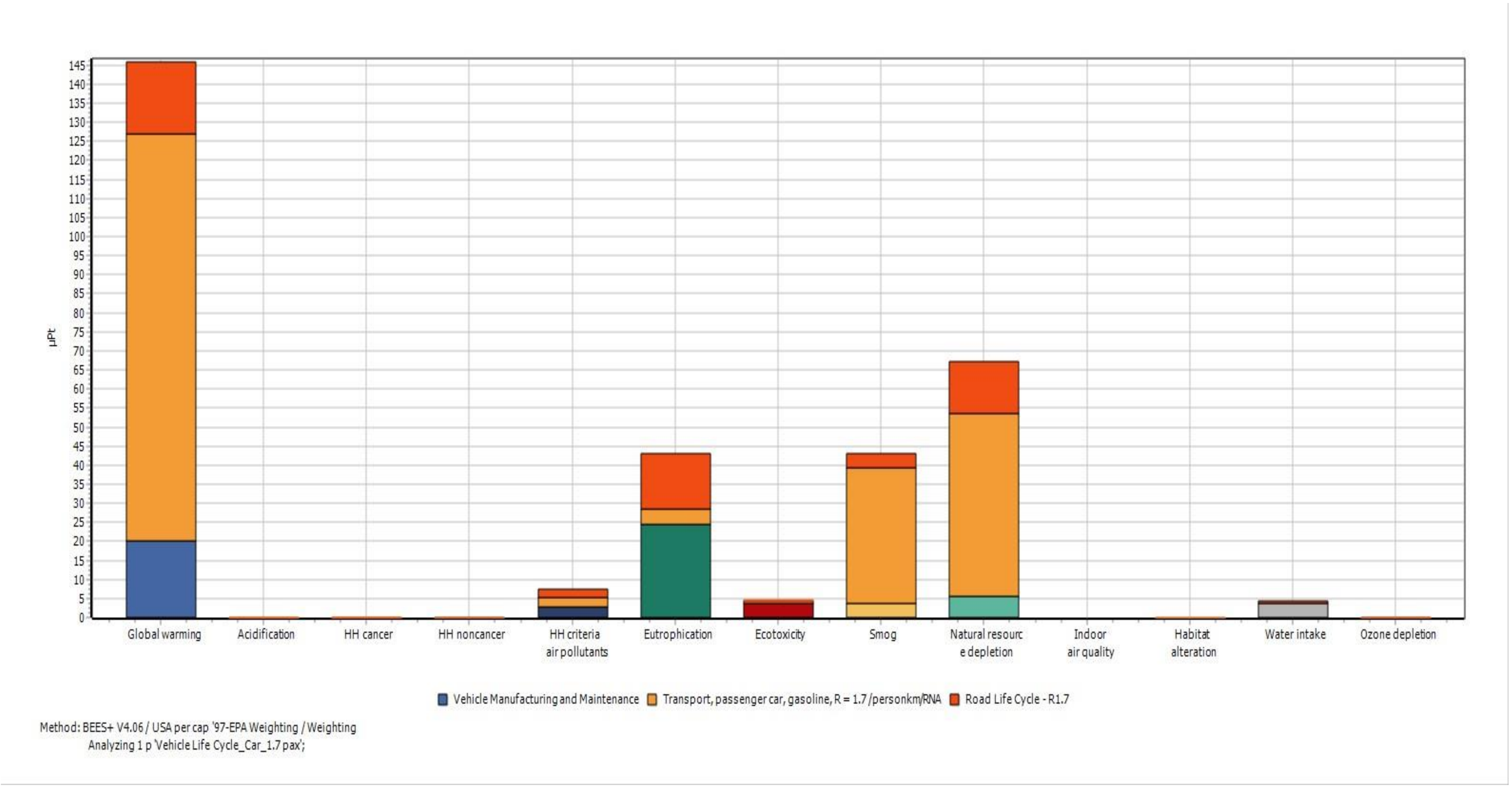
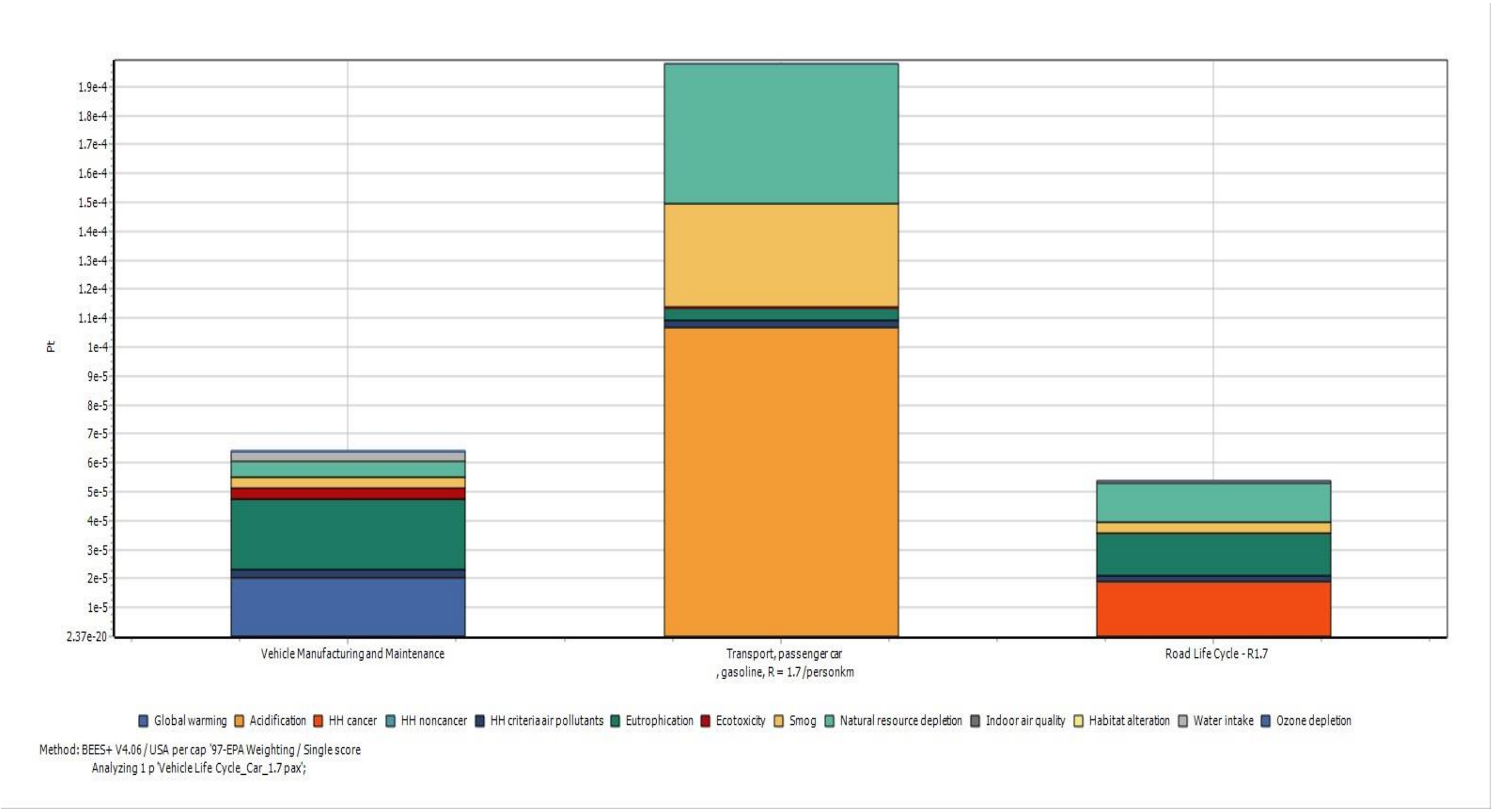


Figure 4-39. Car, Base Case, Weighting, BEES+ (Simapro software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Single score
Analyzing 1 p 'Vehicle Life Cycle_Car_1.7 pax';

Figure 4-40. Car, Base Case, Single Score, BEES+ (Simapro software).

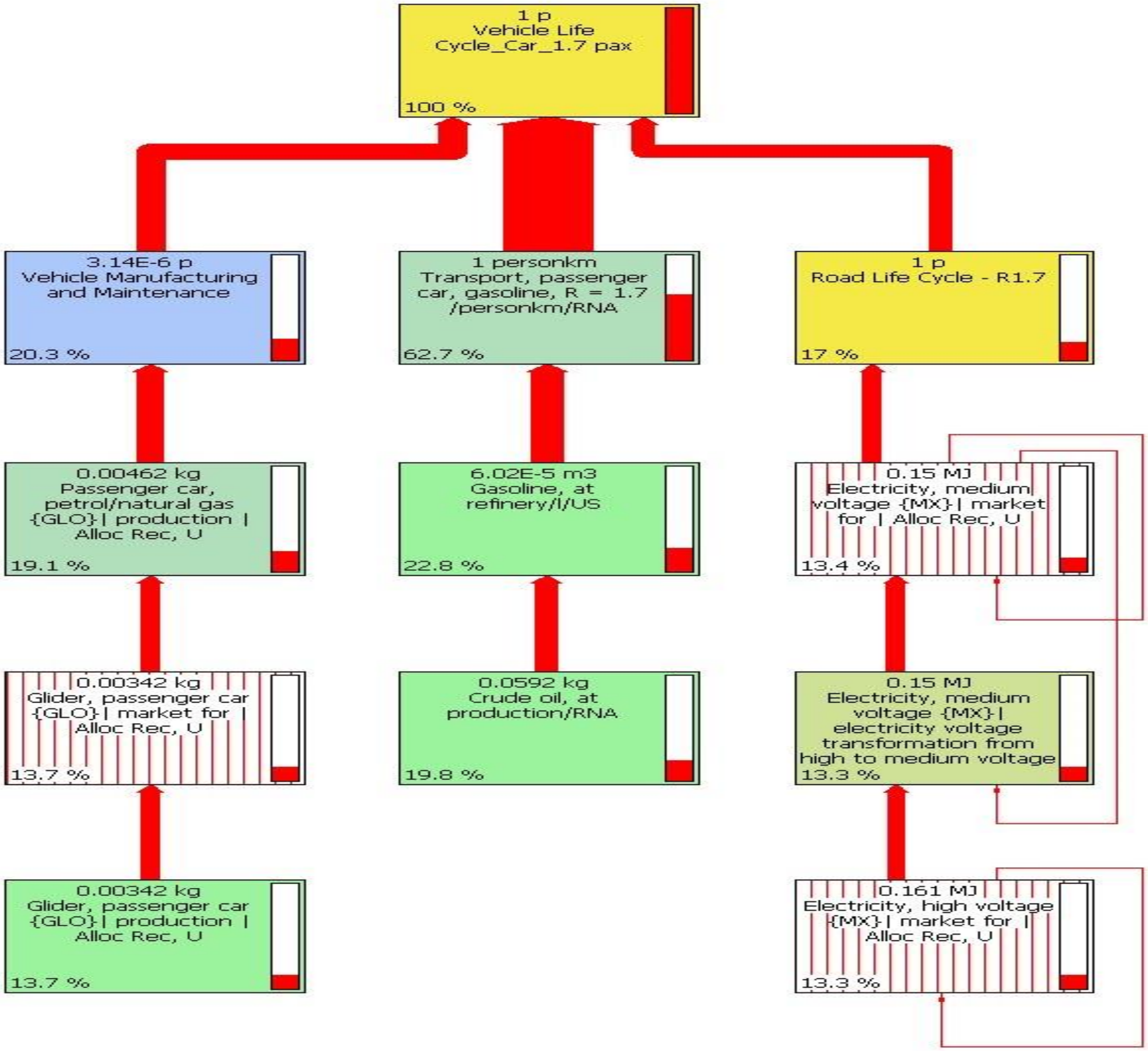


Figure 4-41. Car, Base Case, Network for Single Score, BEES+ (Simapro software).

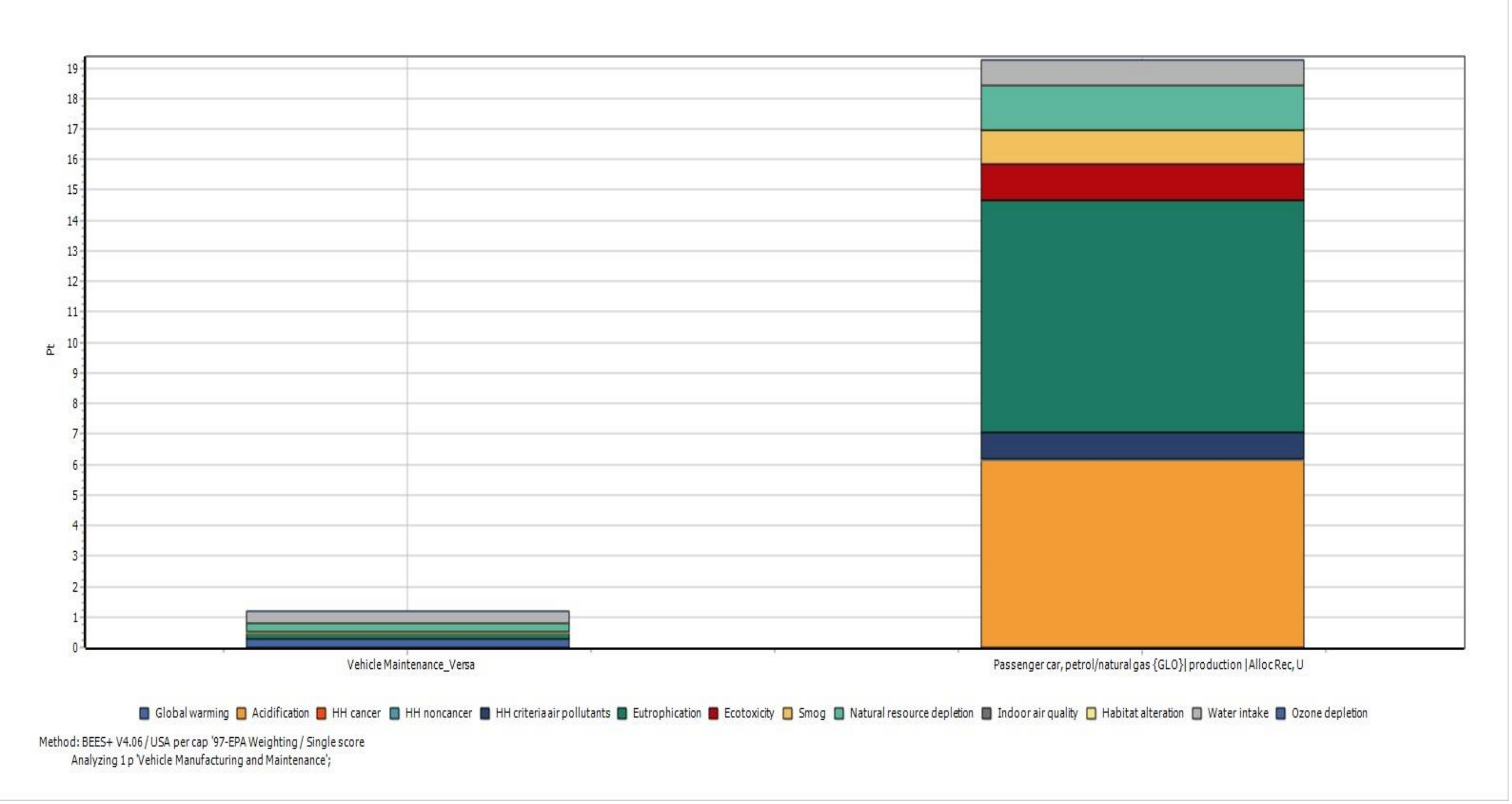


Figure 4-42. Car, Base Case, Vehicle Manufacturing and Maintenance, Single Score, BEES+. (Simapro software)

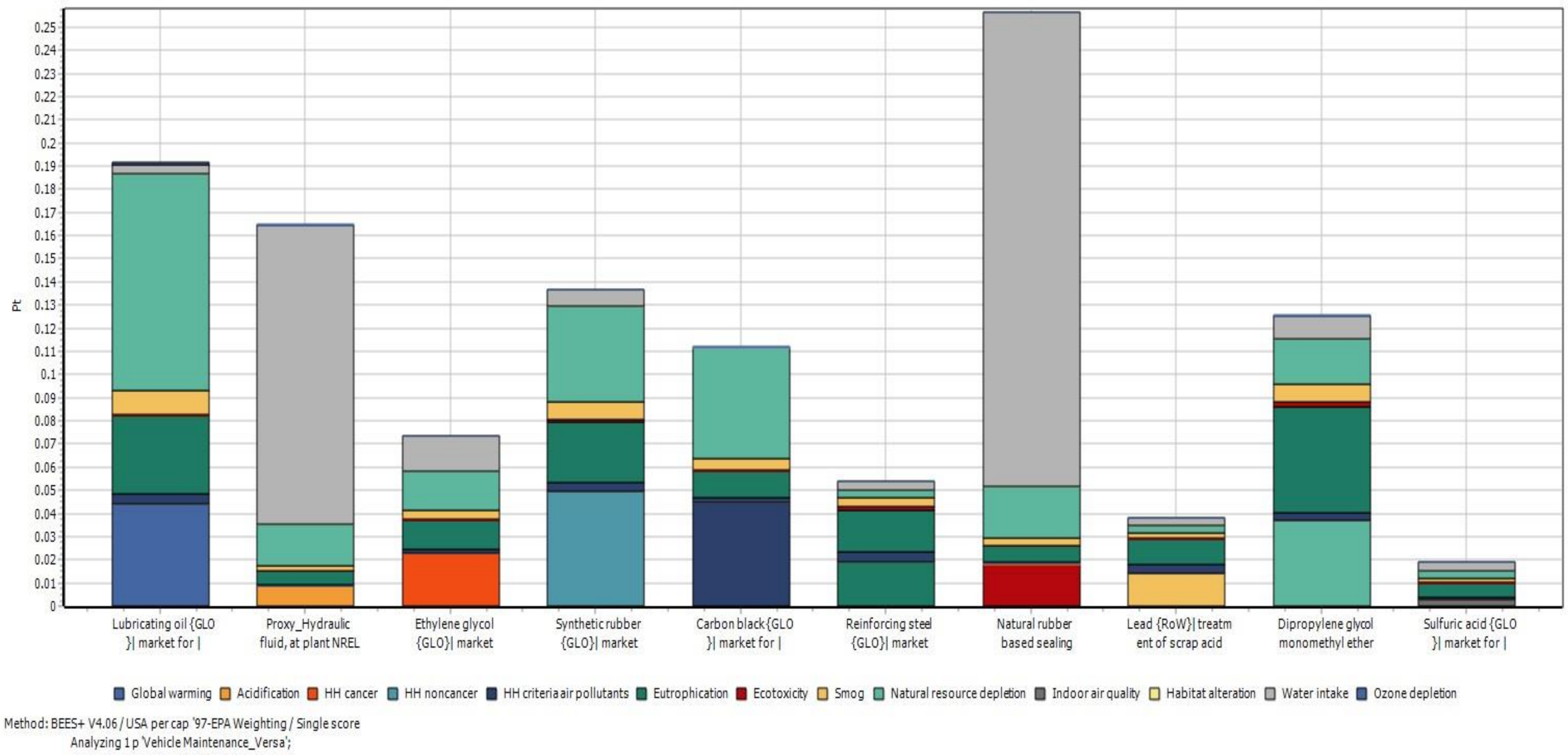


Figure 4-43. Car, Base Case, Vehicle Maintenance, Single Score, BEES+ (Simapro software).

4.4 Results for Research Objective 2, Part 3 (Case Study for Mexico City, Subway)

The method chosen to conduct the impact assessment portion of the subway's LCA was also the BEES+ method.

4.4.1 Inventory Analysis for the Subway

Table 4-14 presents the inventory of greenhouse gases and criteria air pollutants (CAP) from the subway's base case, as well as the percentage contributions to the inventory of the main modules in the system: the vehicle operation, and the station, depot and railway modules. It can be observed that the train's operation contributes 96.90% of the NO_x emissions, in spite of no fuel being combusted onsite, because these are upstream emissions, generated at the point of electricity production, i.e., at the power plants. The railway life cycle generates 1.16% of NO_x and the Station's Life Cycle an additional 1.68% of nitrogen oxides. On the other hand, regarding nitrogen dioxide, the railway life cycle is almost single-handedly responsible for generating them, with 50.50% of these emissions. Additionally, the railway generates the vast majority of PM_{10}, 81.35%, even above the station's (or depot's) contribution to particulates. While the station's contribution to PM_{10} is not insignificant, at 15.75%, presumably most of it resulting from the station's construction at the beginning of the system's life cycle, we again observe the phenomenon that the incremental, albeit daily and continuous, use of an infrastructure module, accumulates and ends up being more significant than one-time or one-season events, when considered over the system's lifetime. In this case, the railway's constant use, tear and wear eventually becomes more significant than the use of the buildings (station or depot) in spite of being much lower in mass, initially. This is akin to what occurred with the illumination of the road or the infrastructure modules in the case of the BRT and the car: daily usage eventually surpasses the inventory, and the impacts, generated by the construction of the infrastructure.

4.4.2 Impact Assessment for the Subway

Figure 4-44 to Figure 4-47 show the results of the characterization, normalization, weighting and single score phases of the BEES+ method applied to the subway's base case. These figures again demonstrate that the vehicle operation dominates the impacts across all categories, and as particularly Figure 4-46 shows, the category with the greatest impact is global warming, followed by eutrophication, natural resource depletion and smog. This is also made clear in Table 4-15, which also shows that while the life cycles for the station, depot and railway do have impacts, and in a similar order of magnitude among themselves, it is the fact that their impacts are three to four orders of magnitude lower than those of the vehicle's operation, which explains why the vehicle's operation predominates in this LCA, in all environmental impact categories. Similarly, the train manufacturing and maintenance module does have impacts, although when they are normalized to the system's life cycle, they result in ten or more orders of magnitude lower than the vehicle's operation. Hence, their impacts appear to fade away, from the viewpoint of an entire life cycle analysis.

Figure 4-48 presents the network diagram for the single score phase of the BEES+ assessment of the subway's base case, at 0.5% cutoff. In this diagram, "Transport," or the vehicle operation, accounts for 98.1% of the single score impact, while the railway's life cycle is 0.633% of the single score and the station's life cycle accounts for 1.11% of the environmental impact, as measured in this single score.

Overall, and in summary, the most significant impact for the subway, assessed by all methods, is that of the secondary emissions resulting from energy production for the train's operation. This means that there is a high potential for improvement associated with energy consumption for the subway system. Reducing energy consumption will reduce the substantial emissions caused by energy production and consumption.

Additionally, an Environmental Impact Assessment was run on each individual infrastructure module, i.e., on a unit kilometer of railway, on a single subway station, and on a single depot. Figure 4-49 shows the single score results of the BEES+ method applied to a single subway depot. In this figure, Portland cement is observed to be the greatest contributor to impacts, followed by the marble flooring (“natural stone”) and by the gravel in third place. While excavation activities are also contributors, their impact decreases over the lifetime of the station due to their occurrence mostly at its beginning. Figure 4-50 presents the results at the single score phase of BEES+ of a unit kilometer railway. In this case, the ballast’s gravel is the greatest contributor, followed by the impacts of Portland cement and of excavation, respectively. Figure 4-51 shows the impact assessment results, at the single score phase of BEES+, for a single subway depot. These results are very similar to those of the station, as expected, since both were calculated with basically the same construction assumptions. For the depot, Portland cement is once again the greatest contributor, followed by the marble flooring (“natural stone”) and in the third place, by the gravel.

Table 4-14. Subway, Base Case, Inventory of Airborne Pollutants: Greenhouse Gases and Criteria Air Pollutants.

Substance	Unit	Total	Train Manuf. & Maint. R=1530	Transport, pass. train urban edited Mexican electricity, R = 1530	Railway Life Cycle R=1530	Station Life Cycle R=1530	Depot Life Cycle R=1530	Vehicle Operation Percentage	Railway Percentage	Station Percentage	Depot Percentage
Carbon dioxide, fossil	kg	7.58E-03	5.69E-16	7.41E-03	4.21E-05	1.15E-04	1.77E-05	97.70%	0.56%	1.51%	0.23%
Carbon monoxide, fossil	kg	2.82E-06	4.72E-18	2.51E-06	1.62E-07	1.28E-07	1.97E-08	89.03%	5.75%	4.52%	0.70%
Dinitrogen monoxide	kg	8.78E-07	2.16E-20	8.75E-07	1.14E-09	1.67E-09	2.72E-10	99.65%	0.13%	0.19%	0.03%
Hydrocarbons, aromatic	kg	8.73E-08	6.46E-21	8.71E-08	1.21E-10	1.42E-10	2.23E-11	99.67%	0.14%	0.16%	0.03%
Hydrocarbons, chlorinated	kg	1.51E-11	1.27E-22	1.06E-11	2.11E-12	2.13E-12	3.28E-13	69.89%	13.90%	14.05%	2.16%
Hydrocarbons, unspecified	kg	6.29E-11	9.03E-23	3.25E-12	5.95E-11	9.80E-14	1.54E-14	5.16%	94.66%	0.16%	0.02%
Lead	kg	1.60E-09	5.00E-21	1.48E-09	5.48E-11	5.90E-11	9.44E-12	92.32%	3.41%	3.68%	0.59%
Nitrogen dioxide	kg	6.83E-08	0.00E+00	0.00E+00	3.45E-08	2.87E-08	5.11E-09	0.00%	50.50%	42.02%	7.48%
Nitrogen oxides	kg	1.48E-05	1.60E-18	1.44E-05	1.72E-07	2.49E-07	3.87E-08	96.90%	1.16%	1.68%	0.26%
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	2.01E-06	7.96E-19	1.94E-06	3.04E-08	2.97E-08	4.67E-09	96.78%	1.51%	1.48%	0.23%
Ozone	kg	5.73E-08	1.81E-21	5.71E-08	6.19E-11	1.29E-10	2.05E-11	99.63%	0.11%	0.23%	0.04%
Particulates, < 10 µm	kg	1.43E-10	0.00E+00	0.00E+00	1.16E-10	2.25E-11	4.15E-12	0.00%	81.35%	15.75%	2.90%
Particulates, < 2.5 µm	kg	1.45E-05	7.24E-19	1.43E-05	3.57E-08	1.29E-07	2.09E-08	98.72%	0.25%	0.89%	0.14%
Particulates, > 2.5 µm, and <10 µm	kg	8.19E-06	5.46E-19	7.98E-06	1.86E-08	1.71E-07	2.82E-08	97.34%	0.23%	2.09%	0.34%
Sulfur dioxide	kg	3.10E-05	3.36E-18	3.07E-05	1.05E-07	1.86E-07	2.94E-08	98.97%	0.34%	0.60%	0.09%
Sulfur hexafluoride	kg	2.88E-09	5.76E-23	2.88E-09	1.80E-12	4.06E-12	6.44E-13	99.77%	0.06%	0.14%	0.02%
VOC, volatile organic compounds	kg	7.52E-11	6.08E-24	0.00E+00	7.43E-11	7.62E-13	1.40E-13	0.00%	98.80%	1.01%	0.19%

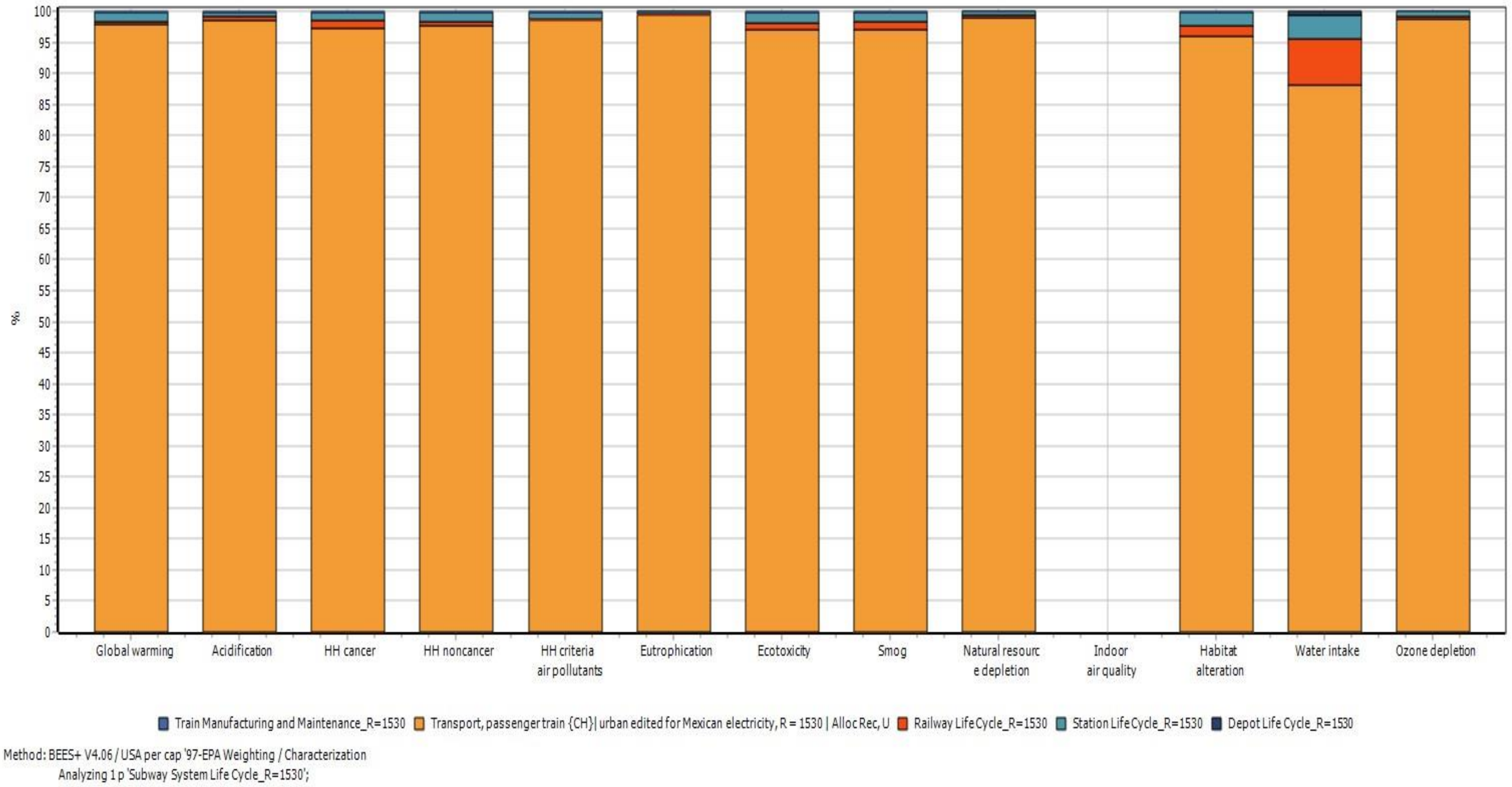


Figure 4-44. Subway, Base Case, Characterization, BEES+ (Simapro software).

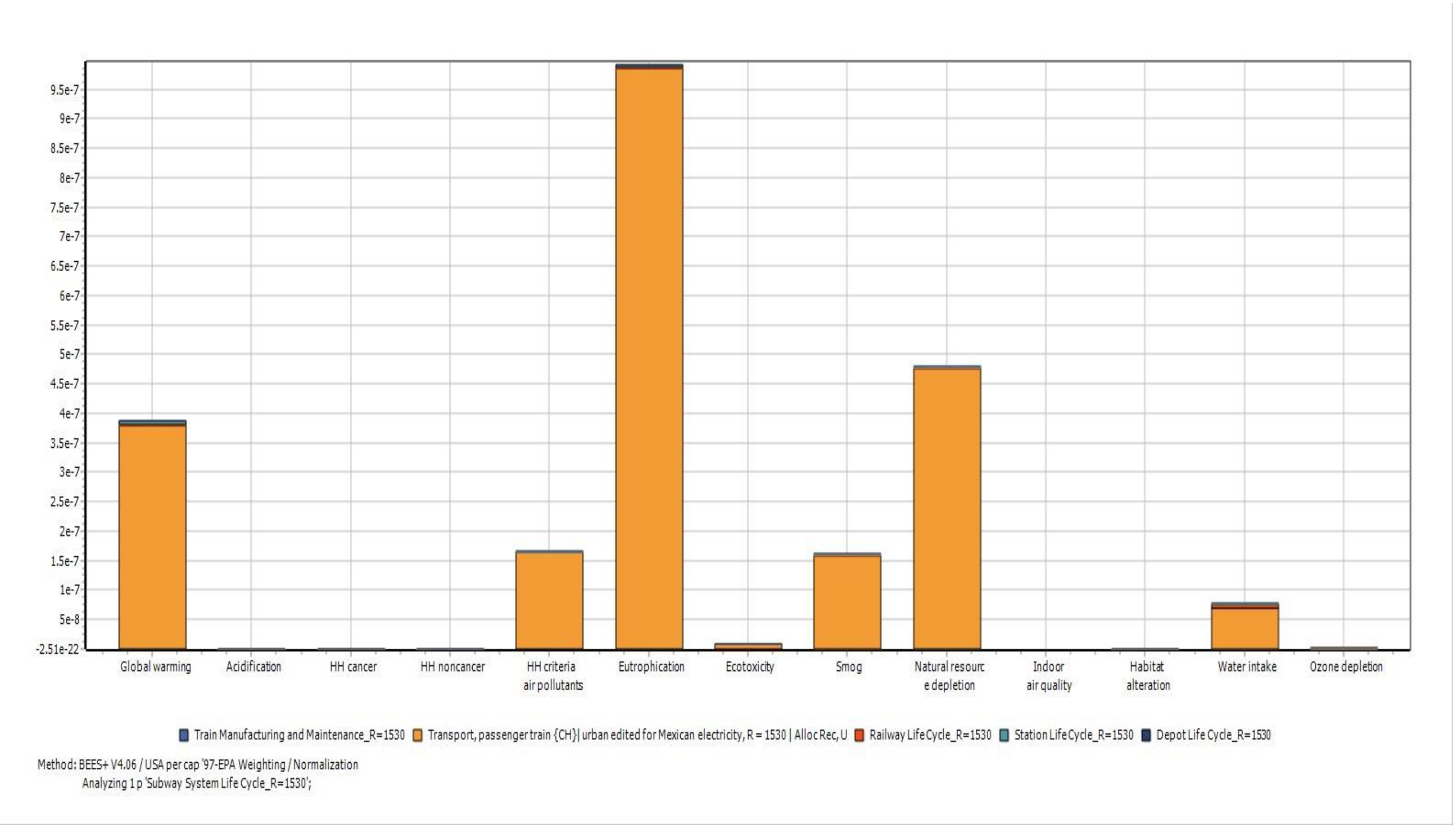


Figure 4-45. Subway, Base Case, Normalization, BEES+ (Simapro software).

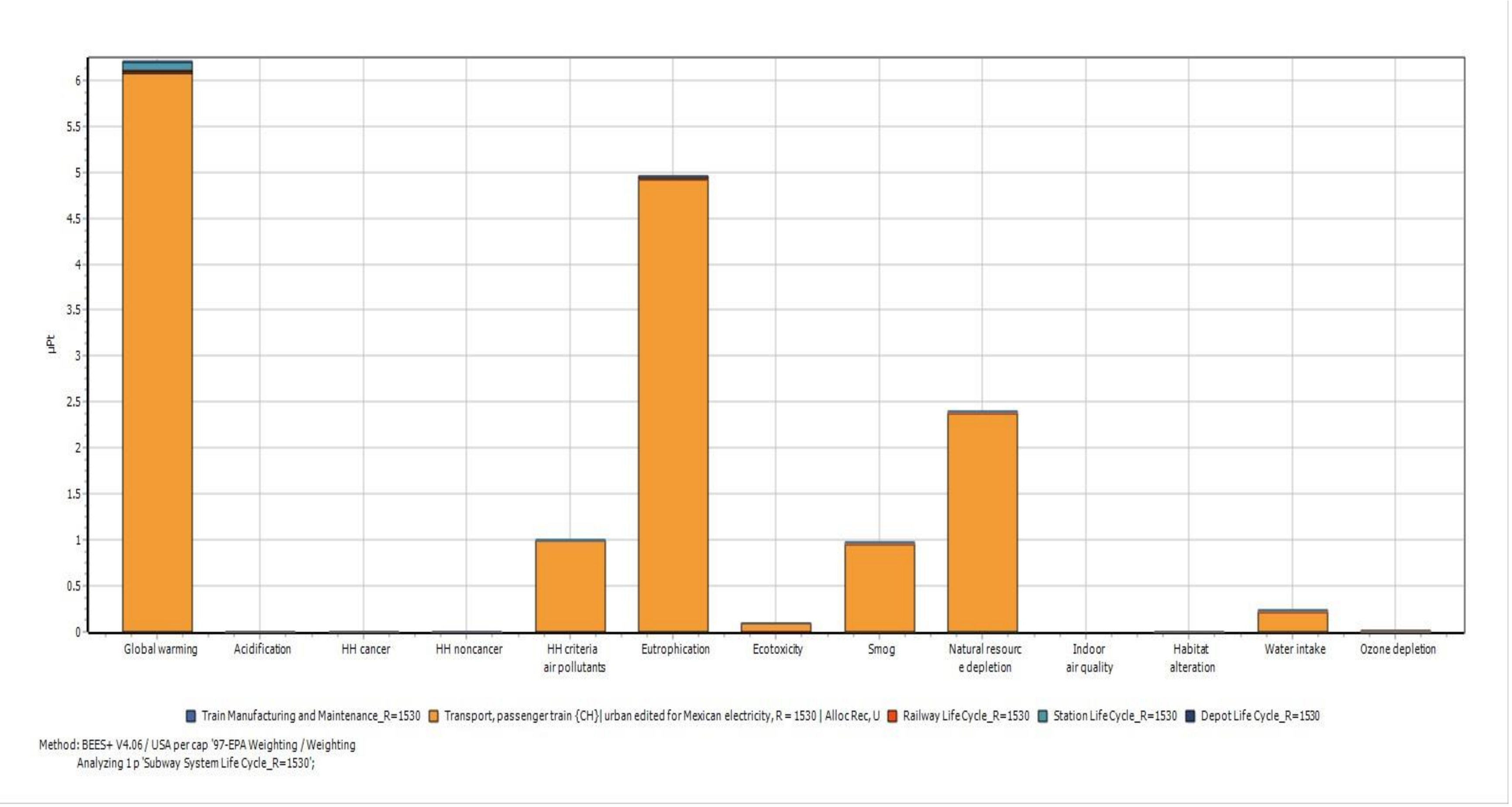


Figure 4-46. Subway, Base Case, Weighting, BEES+ (Simapro software).

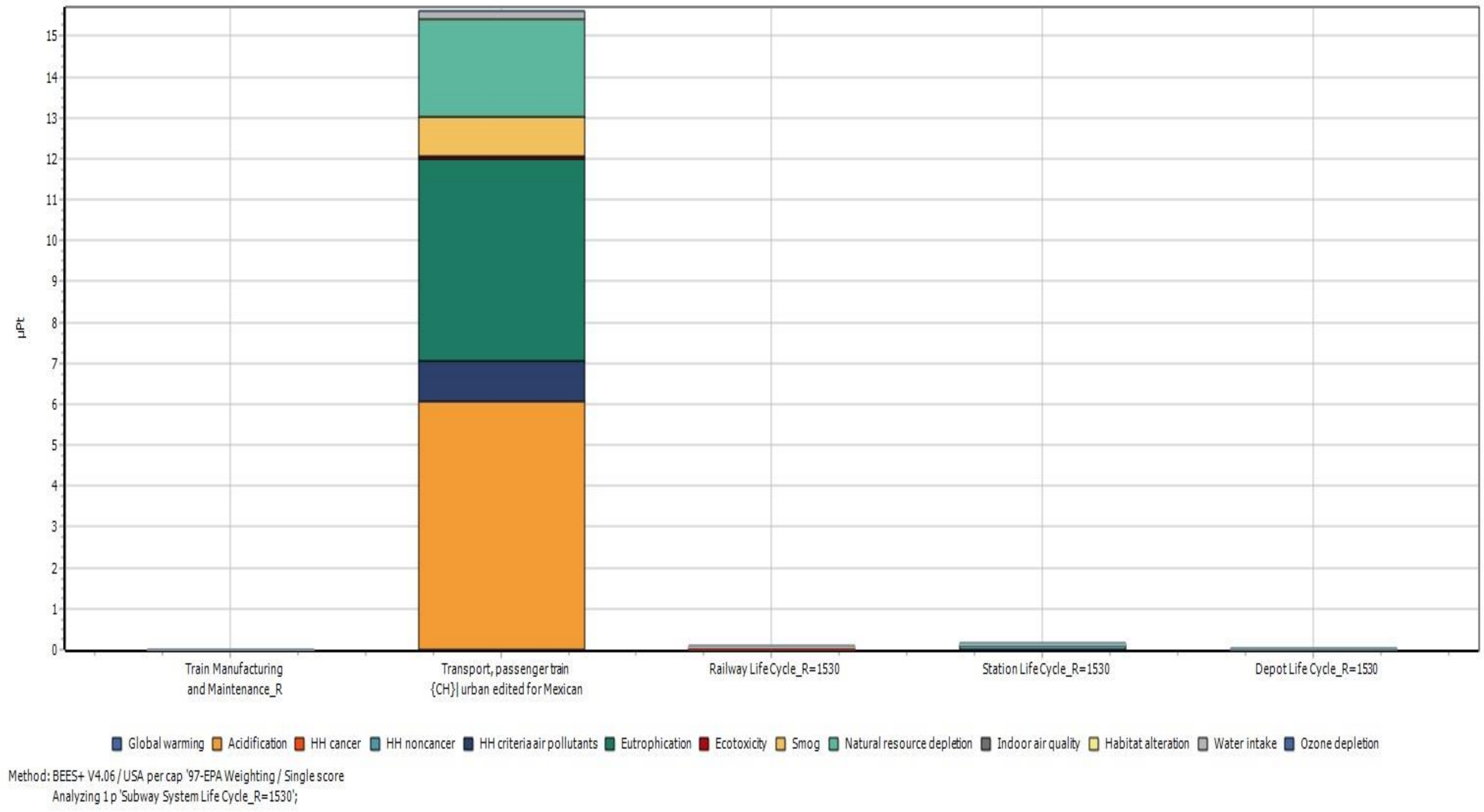


Figure 4-47. Subway, Base Case, Single Score, BEES+ (Simapro software).

Table 4-15. Impact Categories for Subway Base Case, Single Score, BEES+ Method.

Impact category	Unit	Total	Train Manuf. & Maint. R=1530	Transport, pass. Train urban edited for Mexican electricity, R = 1530	Railway Life Cycle R=1530	Station Life Cycle R=1530	Depot Life Cycle R=1530
Total	Pt	1.59E-05	1.62E-18	1.56E-05	8.83E-08	1.55E-07	2.44E-08
Global warming	Pt	6.21E-06	4.62E-19	6.07E-06	3.49E-08	8.78E-08	1.38E-08
Acidification	Pt	1.75E-09	1.84E-22	1.73E-09	9.44E-12	1.43E-11	2.26E-12
HH cancer	Pt	3.87E-09	3.28E-21	3.76E-09	4.56E-11	5.00E-11	7.71E-12
HH noncancer	Pt	1.57E-09	9.12E-22	1.53E-09	1.20E-11	2.24E-11	3.48E-12
HH criteria air pollutants	Pt	9.98E-07	7.41E-20	9.83E-07	2.71E-09	1.09E-08	1.77E-09
Eutrophication	Pt	4.96E-06	7.50E-19	4.92E-06	1.14E-08	1.93E-08	3.03E-09
Ecotoxicity	Pt	9.36E-08	3.40E-20	9.09E-08	8.37E-10	1.61E-09	2.53E-10
Smog	Pt	9.74E-07	9.75E-20	9.46E-07	1.10E-08	1.48E-08	2.34E-09
Natural resource depletion	Pt	2.4E-06	1.22E-19	2.37E-06	9.91E-09	1.18E-08	1.89E-09
Indoor air quality	Pt	0	0	0	0	0	0
Habitat alteration	Pt	2.3E-13	9.89E-26	2.21E-13	4.02E-15	4.54E-15	7.07E-16
Water intake	Pt	2.34E-07	7.58E-20	2.07E-07	1.75E-08	8.92E-09	1.38E-09
Ozone depletion	Pt	8.52E-09	4.64E-22	8.40E-09	4.97E-11	5.77E-11	8.94E-12

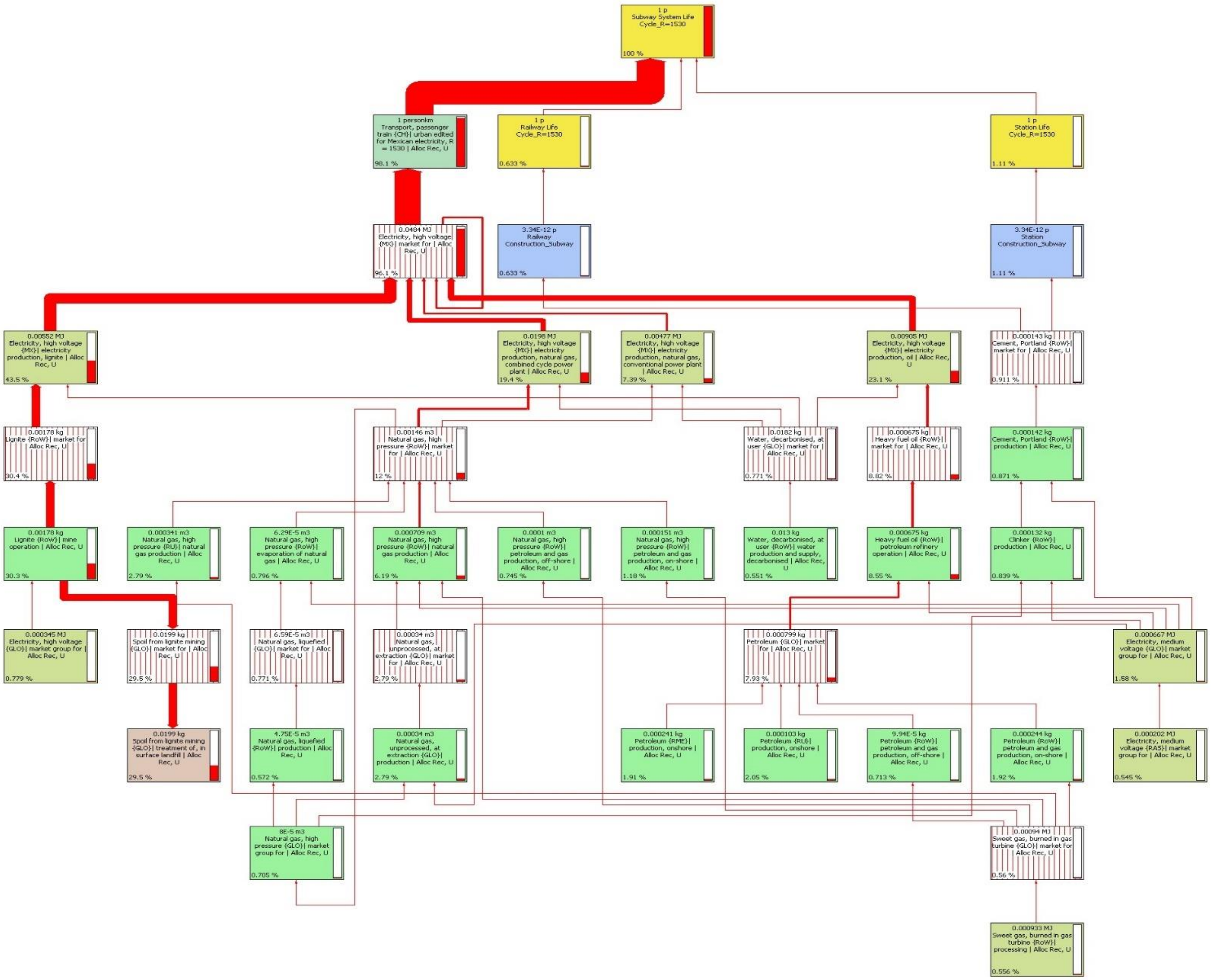


Figure 4-48. Subway, Base Case, Network Single Score, BEES+ (Simapro software).

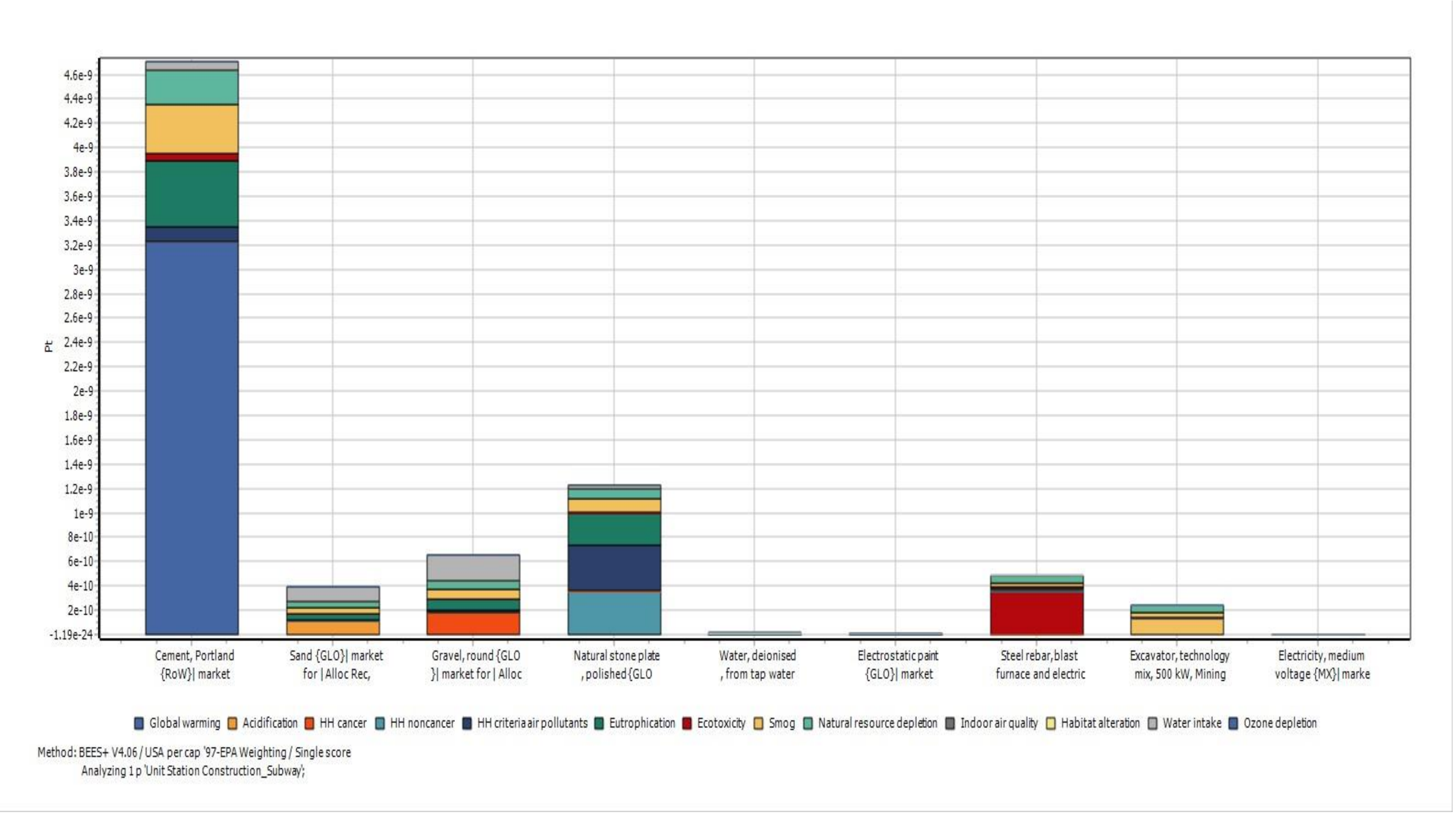


Figure 4-49. Impact Assessment of the Construction of a Station for the Subway, Single Score, BEES+. (Simapro Software).

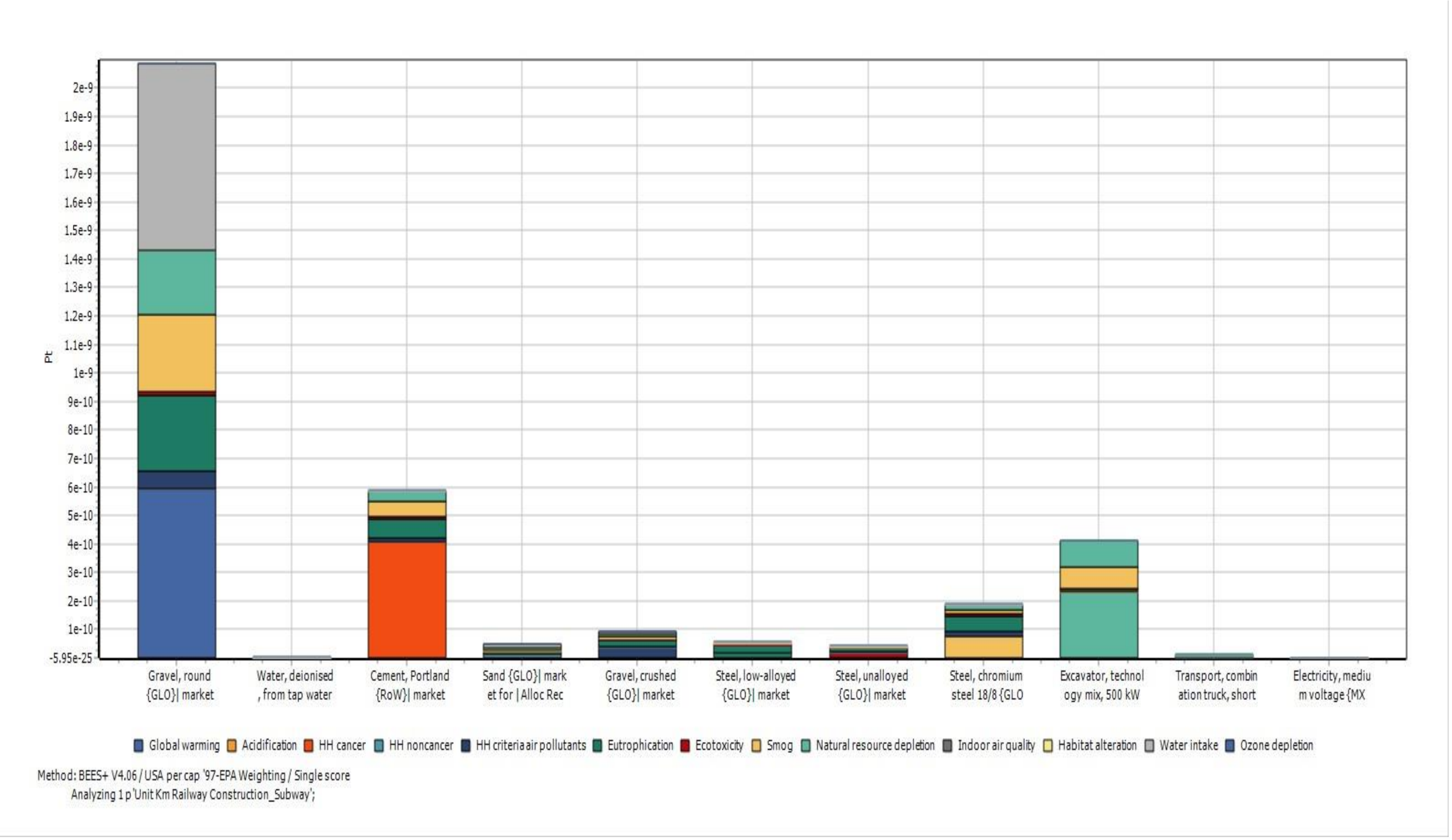


Figure 4-50. Impact Assessment of the Construction of a Unit Kilometer of Rail for the Subway, Single Score, BEES+. (Simapro Software).

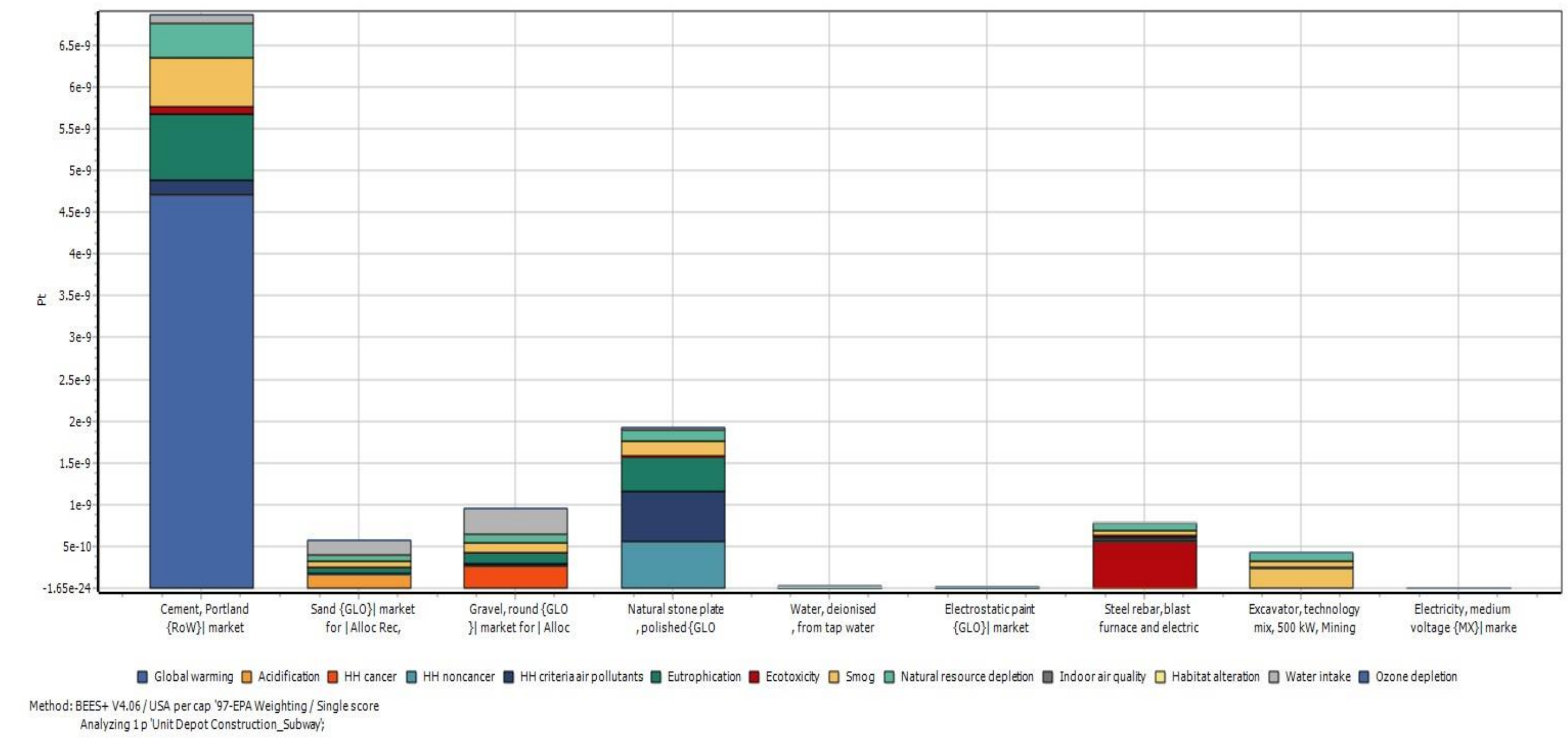


Figure 4-51. Impact Assessment of the Construction of a Depot for the Subway, Single Score, BEES+. (Simapro Software).

4.4.3 Summary Comparison of the LCAs for the Three Transportation Modes

At the level of the single score phase of the BEES+ impact assessment of the three transportation modes of this study, Table 4-16 summarizes the percentage contributions for the vehicle's operation and each of the major infrastructure modules: the road/railway, station and depot for the subway and BRT, and the roadway only for the Car. It is interesting to note the similarity in the percentages for the two onroad methods, in that the fuel subsystem, the combustion of the fuel in the engine, accounts for 62% of the life cycle impact. In the case of the car, since it only has one infrastructure module in that subsystem, the road, its contribution to the life cycle decreases, relative to the BRT's case, rather than increase or remain the same. Thus, the infrastructure subsystem's contribution drops from 34.93% (adding the three modules in this subsystem) in the BRT to only 17% in the car, and for the car, the remaining percent is taken up by the vehicle's manufacturing and maintenance. The greatest contrast is naturally provided by the comparison between both onroad systems and the subway. Resulting mainly of the very large lifetime performance, or lifetime VKT of the subway trains, relative to the BRT and the car, -being at least an order of magnitude greater than the lifetime VKT for the car or the BRT--, it can be seen that the percentage contributions of the infrastructure virtually disappear for the subway. Therefore, only the electricity required for the trains' operation is left as the almost only part responsible for the entire lifecycle environmental impact. Furthermore, an added advantage of the subway relative to the onroad modes is yet another order of magnitude in the larger passenger capacity of the train vis-à-vis the BRT and the car. Hence, when the environmental impacts are first normalized by VKT, and then, by ridership, to obtain an environmental impact assessment in terms of impact per passenger-kilometer, it can be observed that the subway as a mode of transportation starts with an advantage of at least two orders of magnitude over the onroad vehicles. Furthermore, electricity is a "cleaner" or less polluting fuel, relative to fossil fuels. Against this backdrop, it is hardly surprising that the subway is the transportation mode with the lowest impacts. It is also important to note that, and in spite of the subway's infrastructure having required an effort and investment clearly superior than that for the onroad vehicles when it was initially built, over the subway's lifetime, in terms of environmental impacts measured in a per passenger-kilometer basis, that infrastructure investment is recovered many times over.

Table 4-16. Summary of Single Score Impacts for the Three Transportation Modes

Transportation Mode	"Transport" or Vehicle Operation Percentage	Road/Railway Percentage	Station Percentage	Depot Percentage	Vehicle Manufacturing and Maintenance
BRT	65%	22.4%	9.73%	2.8%	0.008%
Car	62.7%	17%	--	--	20.3%
Subway	98.1%	0.633%	1.11%	0.175%	--

4.5 Results for Research Objective 3 (Cumulative Exergy Method and ExLCA)

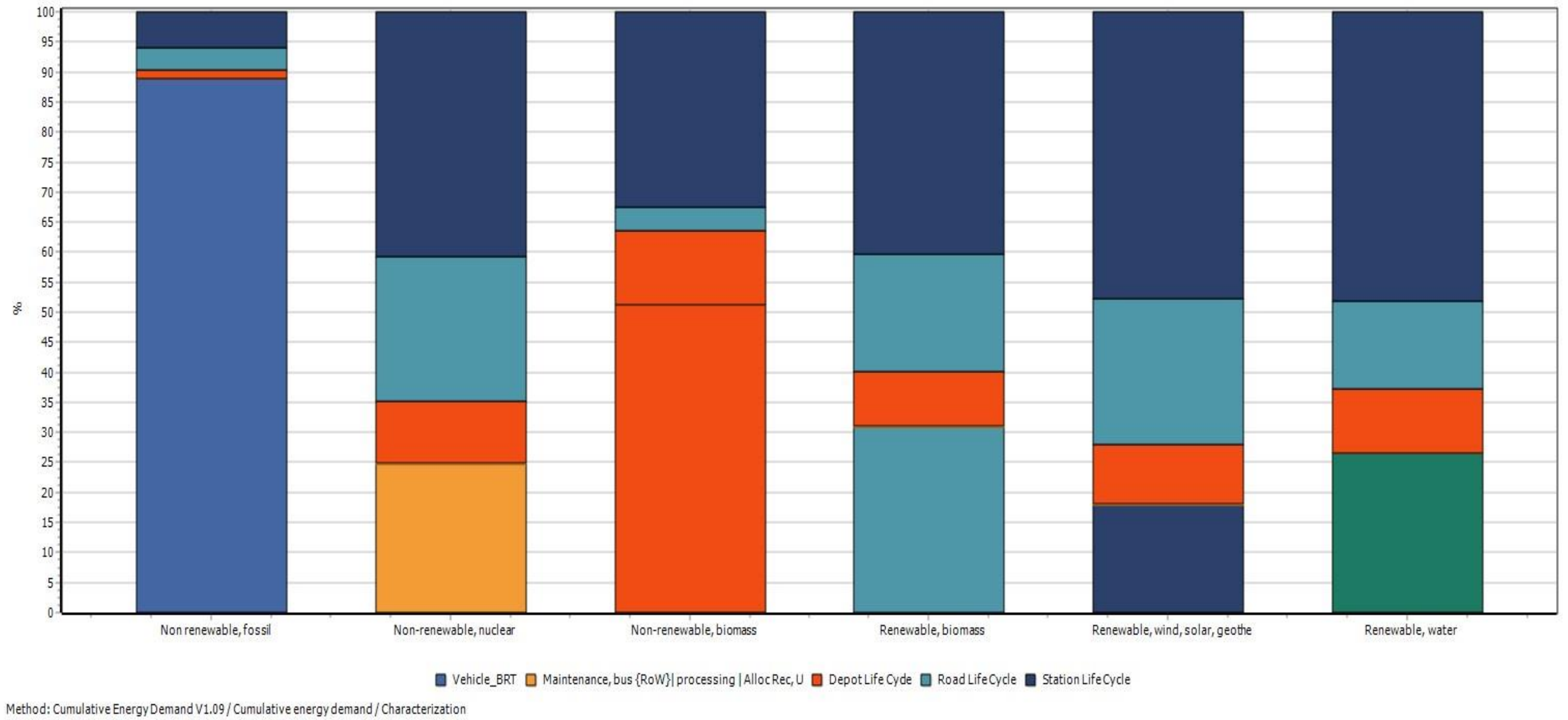
In order to fulfill Objective 3, Simapro's Cumulative Exergy Demand (CExD) method was run for each of the three transportation modes.

4.5.1 Cumulative Exergy Demand for BRT

As prelude to the impact assessment of the BRT system by the Cumulative Exergy Demand (CExD) method as it exists in Simapro, the Cumulative Energy Demand (CED) method was run. Figure 4-52 shows the characterization phase of this CED method, while Figure 4-53 shows the single score of this method. Similarly, Table 4-17 shows the Cumulative Exergy Demand for the BRT system, both in total amount and by subsystem, as well as their corresponding percentages. As expected, the vehicle is the greatest generator of impact, and the "non-renewable, fossil" category is the one with the greatest impact as well. To note, the station’s life cycle is the second contributor to impact, and interestingly, it shows an important contribution in the “renewable, solar, wind, geothermal” category. This is possibly due to the fact that most of the electricity used for the lighting of the station is provided to the Metrobus system in a medium voltage, and this voltage apparently is reported with a higher percentage of renewable energies in the Mexican electricity mix (Santoyo-Castelazo, *op. cit.*).

Figure 4-54 presents the characterization results of the Cumulative Exergy Demand for the BRT system, where it can be observed that the vehicle is the greatest contributor, with the station’s life cycle in a consistent second place, in almost all categories, and with the road’s life cycle in a near third place. Figure 4-55 shows the single score of the Cumulative Exergy Demand, where it can be seen that while the vehicle has the greatest impact, the impact category is the same for all modules: non-renewable, fossil, followed by the non-renewable, nuclear and the non-renewable, metals categories.

Figure 4-56 shows the network diagram for the single score phase of the Cumulative Exergy Demand applied to the BRT’s base case. It can be observed in this diagram that the vehicle accounts for 86.6% of the impact in this method; the station’s life cycle for 7.5% of it, and the road for 4.16%. If these two latter numbers are added, the infrastructure in these conditions represents 11.66% of the total impact. Although no previous LCA in transportation studies have studied exergy, it is interesting to note that this percentage contribution for the infrastructure is approximately the same number as those estimated by other similar transportation LCA studies that included the infrastructure “component” (Chester, 2010).



Method: Cumulative Energy Demand V1.09 / Cumulative energy demand / Characterization
Analyzing 1 p 'BRT_System Life Cycle';

Figure 4-52. BRT Base Case, Characterization, Cumulative Energy Demand (Simapro Software).

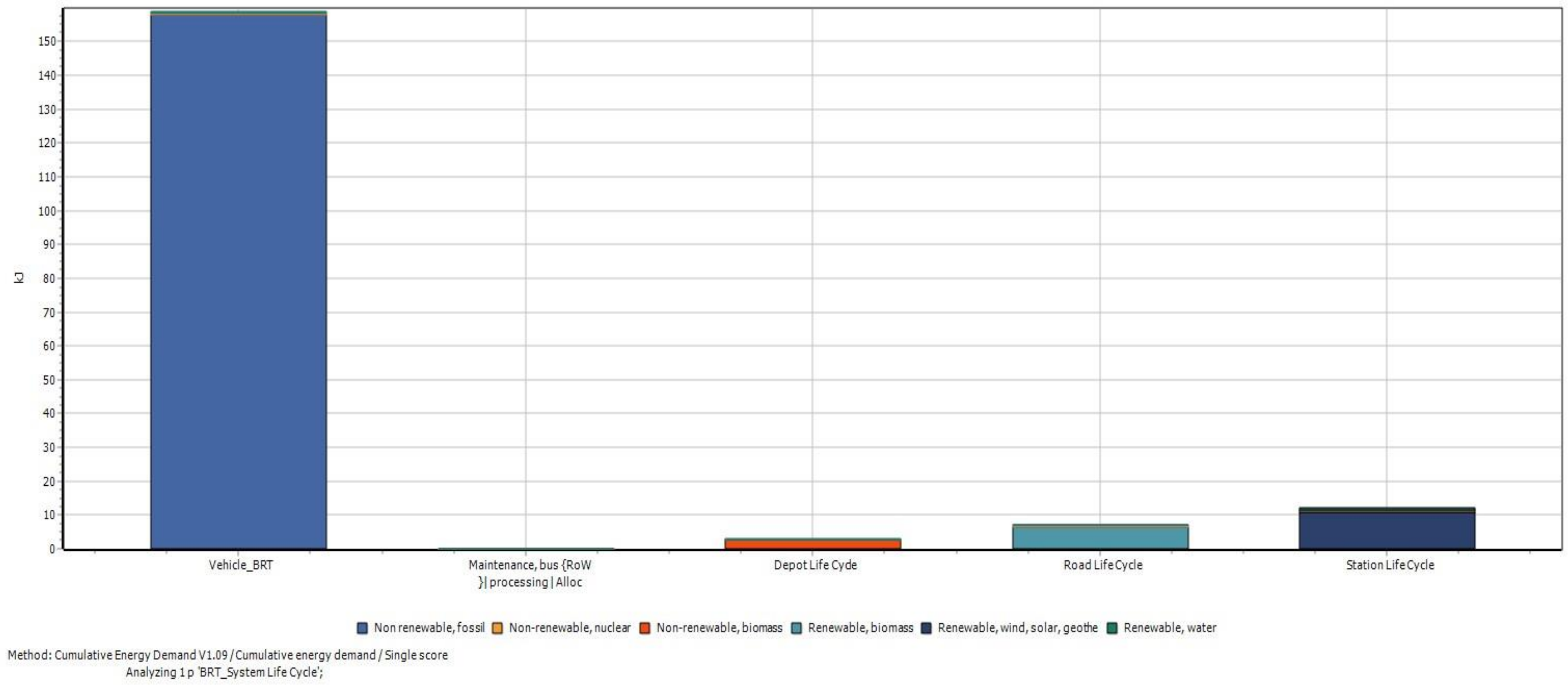


Figure 4-53. BRT Base Case, Single Score, Cumulative Energy Demand (Simapro Software).

Table 4-17. Cumulative Energy Demand for the BRT, Total and by Subsystem.

Impact category	Unit	Total	Vehicle BRT	Maintenance, bus {RoW}| Alloc Rec, U	Depot Life Cycle	Road Life Cycle	Station Life Cycle	Vehicle Percentage	Maintenance Percentage	Depot Percentage	Road Percentage	Station Percentage
Total	kJ	181.4	158.9	0.0255	2.99	7.18	12.30	87.60%	0.01%	1.65%	3.96%	6.78%
Nonrenewable, fossil	kJ	177.8	158.0	0.01990	2.62	6.48	10.72	87.08%	0.01%	1.44%	3.57%	5.91%
Non-renewable, nuclear	kJ	1.54	0.380	0.00360	0.158	0.371	0.630	0.21%	0.00%	0.09%	0.20%	0.35%
Non-renewable, biomass	kJ	0.00176	0.000903	1.262 E-07	0.000218	6.66E-05	0.000573	0.00%	0.00%	0.00%	0.00%	0.00%
Renewable, biomass	kJ	0.456	0.141	0.000487	0.0419	0.0893	0.184	0.08%	0.00%	0.02%	0.05%	0.10%
Renewable, wind, solar, geothermal	kJ	0.117	0.0209	0.000264	0.0115	0.0283	0.0556	0.01%	0.00%	0.01%	0.02%	0.03%
Renewable, water	kJ	1.49	0.395	0.001293	0.158	0.217	0.718	0.22%	0.00%	0.09%	0.12%	0.40%

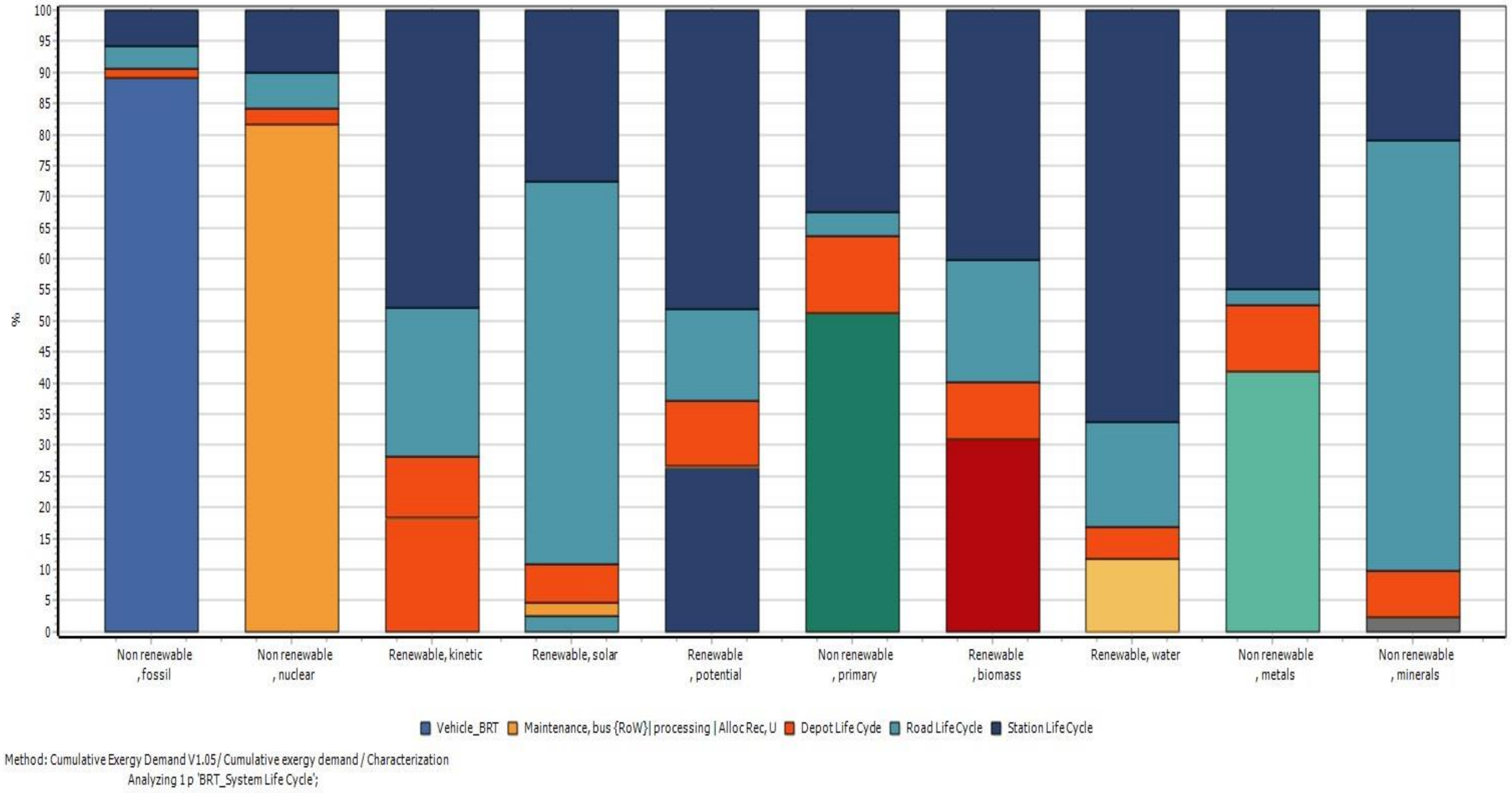


Figure 4-54. BRT, Base Case, Characterization, Cumulative Exergy Demand (Simapro software)

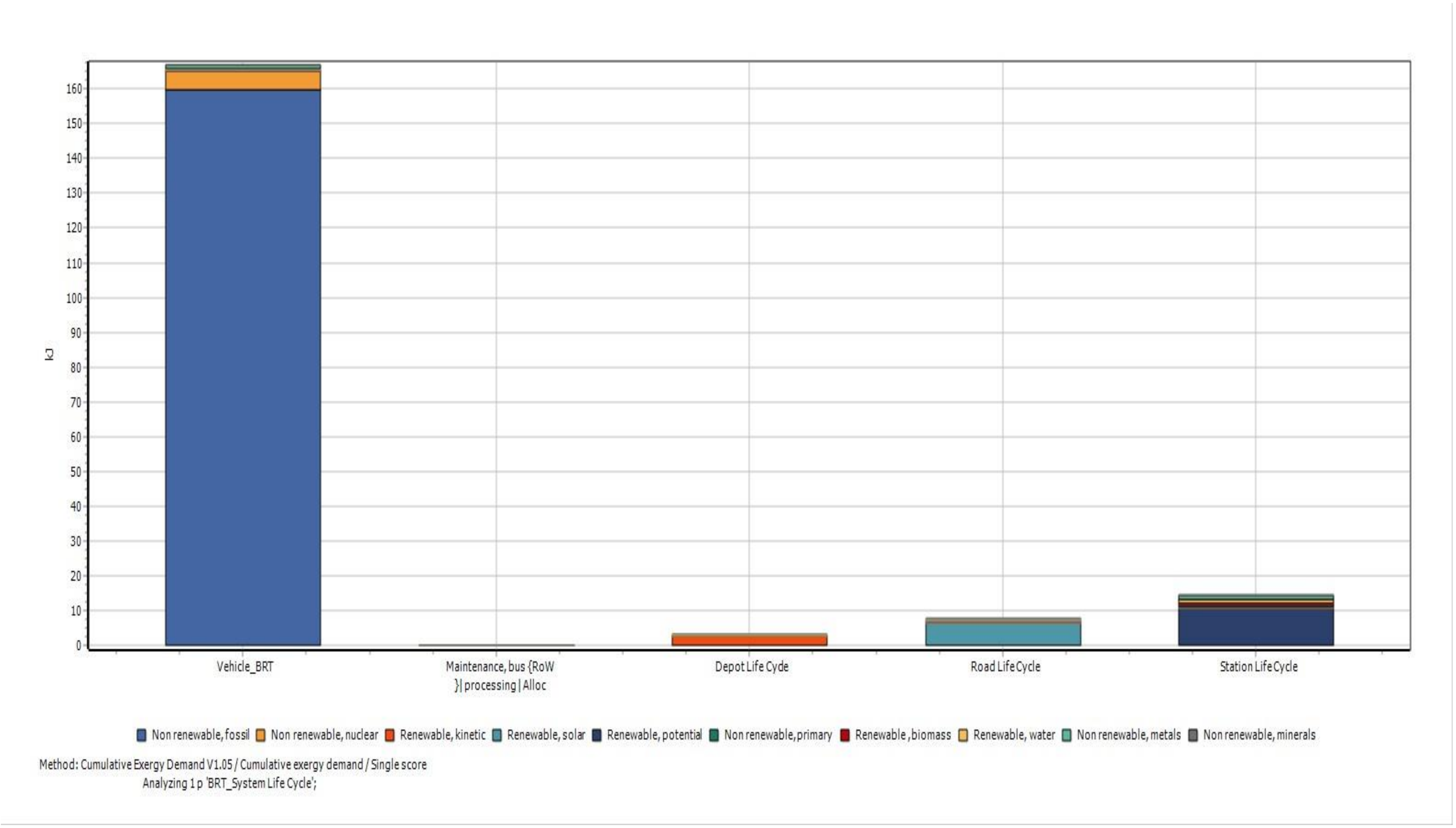


Figure 4-55. BRT, Base Case, Single Score, Cumulative Exergy Demand (Simapro software).

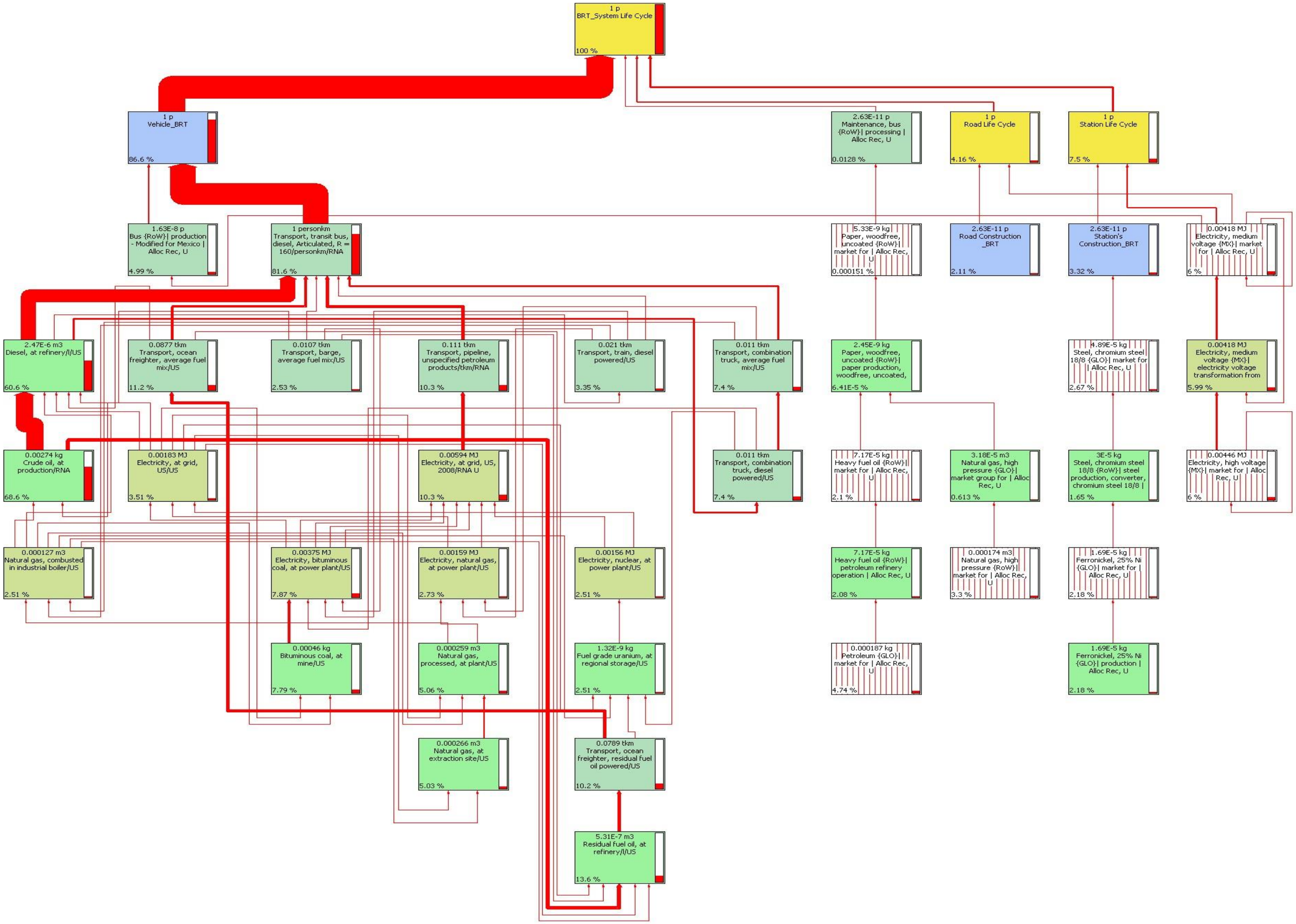


Figure 4-56. BRT, Base Case, Network Single Score, Cumulative Exergy Demand (Simapro software).

4.5.2 Cumulative Exergy Demand for Car

To provide a backdrop against which to measure the Cumulative Exergy Demand, the Cumulative Energy Demand (CED) Environmental Impact Assessment (EIA) method was first run in Simapro. Figure 4-57 and Figure 4-58 show the single score for the Cumulative Energy Demand of the car's Base Case, as well as its Network diagram. In the latter figure, the CED method assigns a value of 67.4% to the impact generated by the "Transport," or vehicle subsystem's operation, 12.5% to the vehicle's manufacturing and maintenance, and a 20.1% of the road. Once again, an EIA method is assigning the second place in impact to the road, and not to the vehicle manufacturing and maintenance.

Figure 4-59 presents the results of the Cumulative Exergy Demand (CExD) method for the car's base case in its characterization phase, and Figure 4-60 is its single score phase. As can be observed, and as expected, the vehicle's operation ("Transport"), accounts for the majority of the exergetic impact, with most from the "non-renewable, fossil" category. Comparison of Figure 4-57 and Figure 4-60, which are the single score for the Cumulative Energy Demand and the Cumulative Exergy Demand respectively, display a virtually identical result, with an interesting exception. For the vehicle's manufacturing and maintenance, the Cumulative Exergy Demand method detects an important contribution in the "non-renewable, metals" category. This is naturally due to the car's battery, which is indeed obtaining work, i.e., exergy, from its sulfuric acid and lead elements. Figure 4-61 shows the network diagram for the single score phase of the Cumulative Exergy Demand method for the car's base case. From this figure it can be seen that the vehicle's operation accounts for 62.1% of the impact in terms of exergy in this system, the vehicle's manufacturing and maintenance for 19.6% and the road's life cycle for 18.3%. These percentages are similar to those obtained in the Cumulative Energy Demand method, except for the vehicle's maintenance and manufacturing's contribution being greater, due to the exergy obtained from the car's battery, mentioned above.

Additionally, and given the importance of exergy to this study's objectives, it was decided to run a sensitivity analysis for exergy utilization only. That is, the exergy demand was measured for the 4 available "products" or cars within this study. These cars have the same weight, lifetime, expected $VKT_{lifetime}$ and differ only by their ridership: from 1 to 1.7 to 3 to 5 passengers. These results are shown in Figure 4-62**Error! Reference source not found.**, the characterization phase, and in Figure 4-63, the single score of the Cumulative Exergy Demand, applied to the four different cars, each with its corresponding ridership. These figures once again ratify the linear relationship of a decreased energy/exergy demand with an increased ridership, and also confirm that the "non-renewable, fossil" category is the one with the greatest impact.

A Cumulative Exergy Demand analysis was also run on the product stage representing the unit kilometer of road, in this case, of flexible pavement, for the car. Figure 4-64 shows the results of this analysis, in the single score phase of this method. Electricity for the road's lighting and bitumen for the asphaltic pavement are again identified as the elements with the greatest impact. An interesting result from this method is that the bitumen's impact, in terms of exergy, is correctly identified mostly within the "non-renewable, primary" category. This of course refers to the fact that asphalt is essentially a petroleum-derived compound, that in spite of having gone through the refinery process is essentially the part that was discarded from it. As such, it is high in hydrocarbons, and can be adequately classified as primary energy.

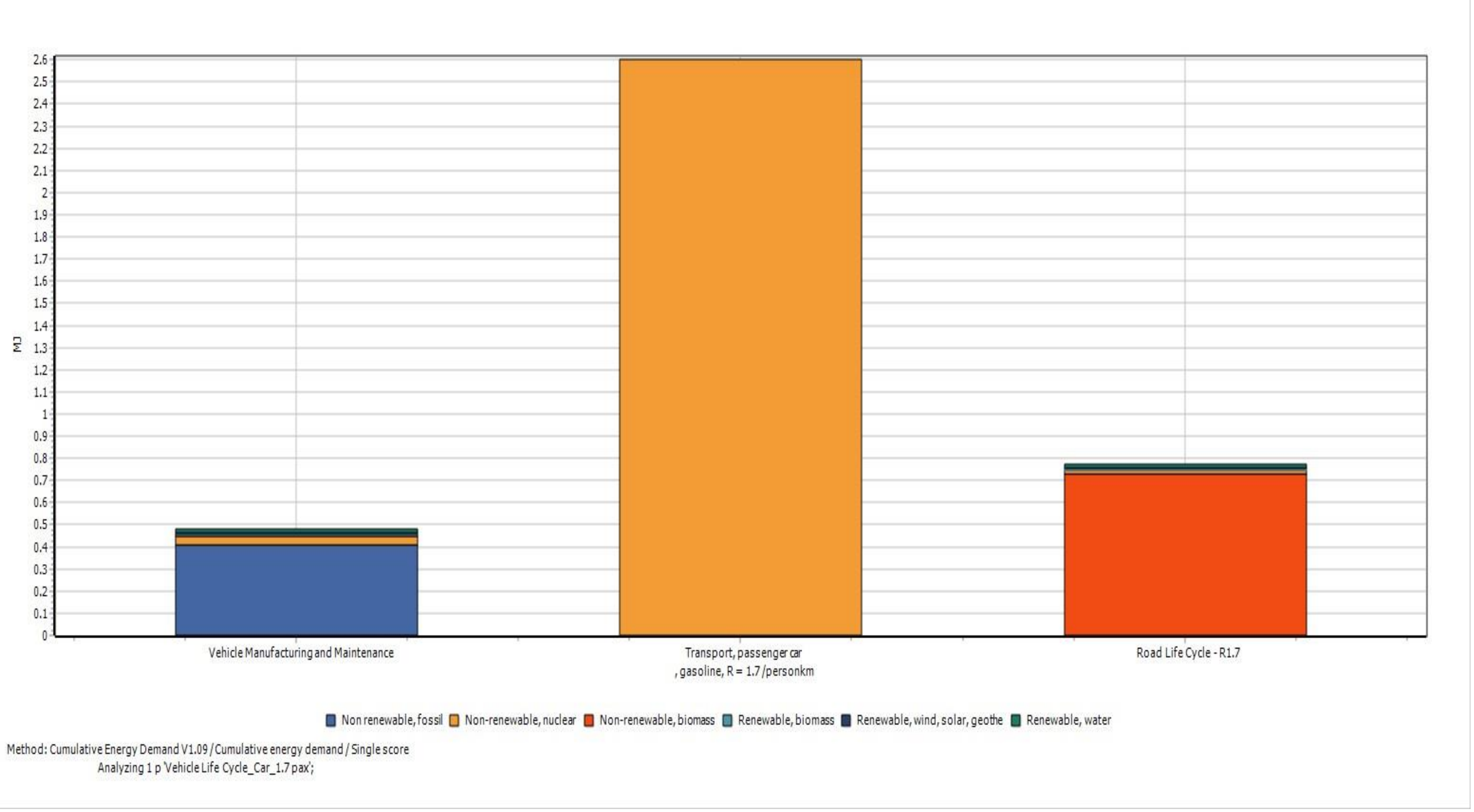


Figure 4-57. Car, Base Case, Single Score, Cumulative Energy Demand. (Simapro software)

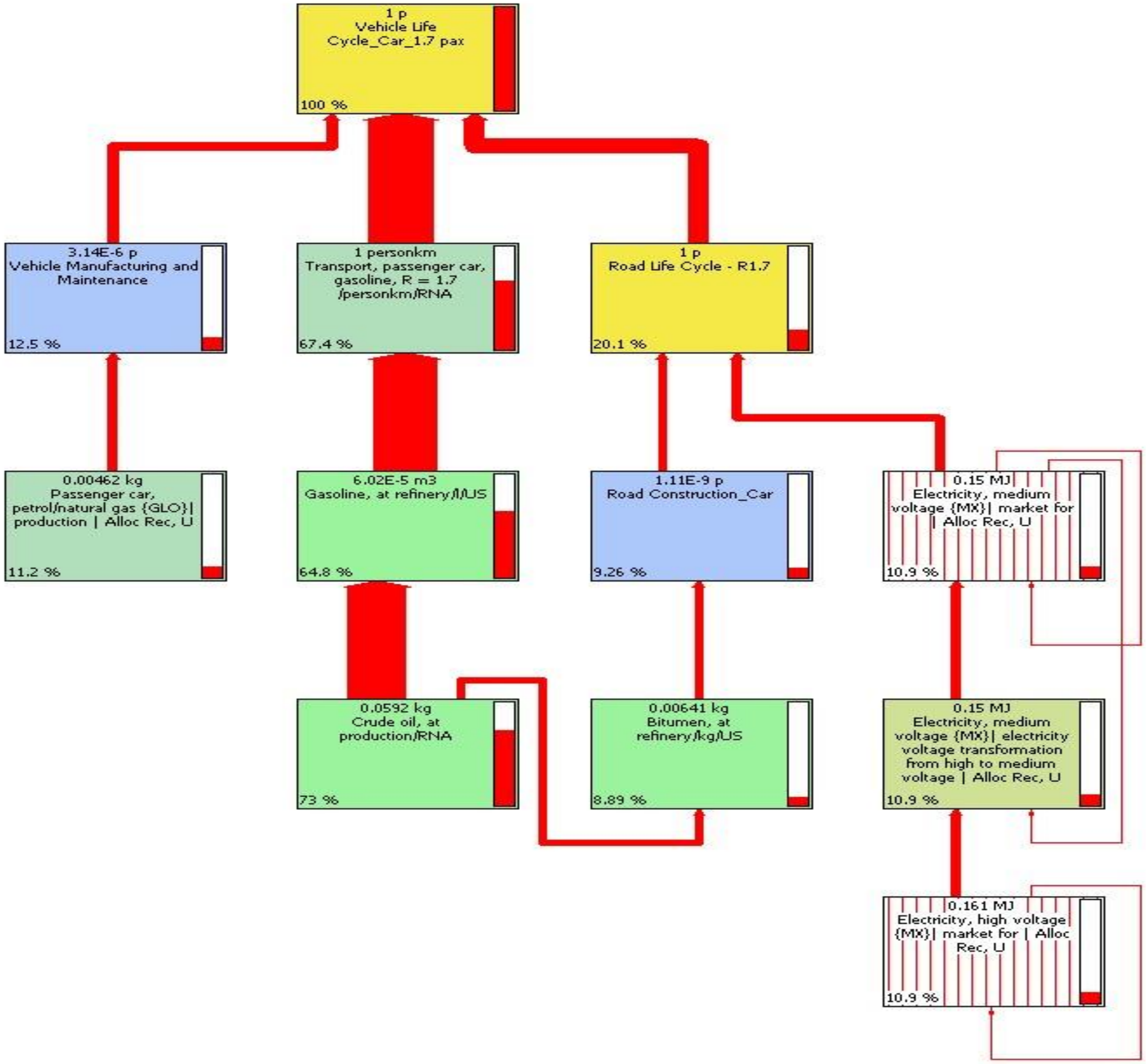


Figure 4-58. Car, Case Base, Network for Single Score, Cumulative Energy Demand. (Simapro software)

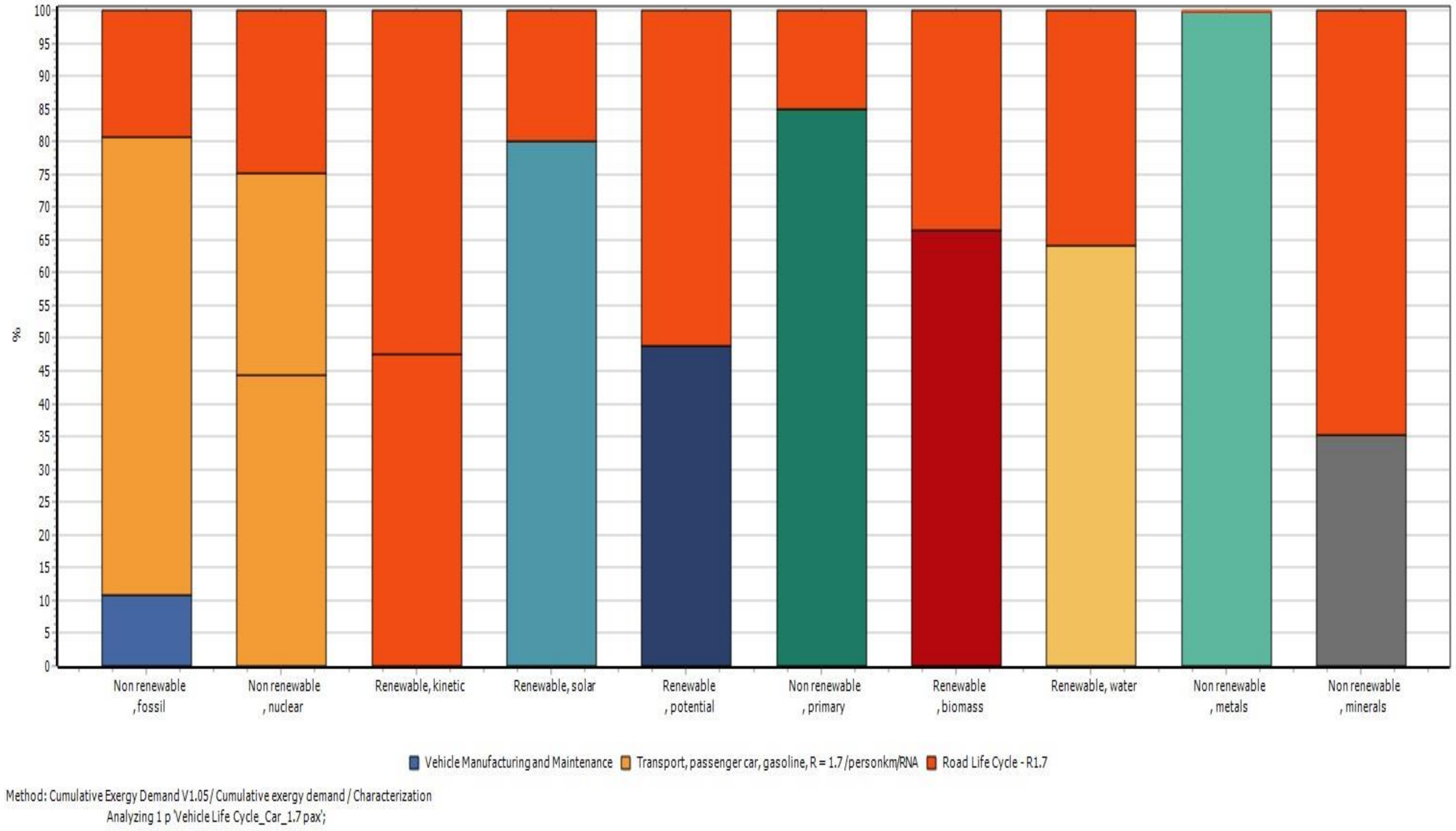


Figure 4-59. Car, Base Case, Characterization, Cumulative Exergy Demand (Simapro software).

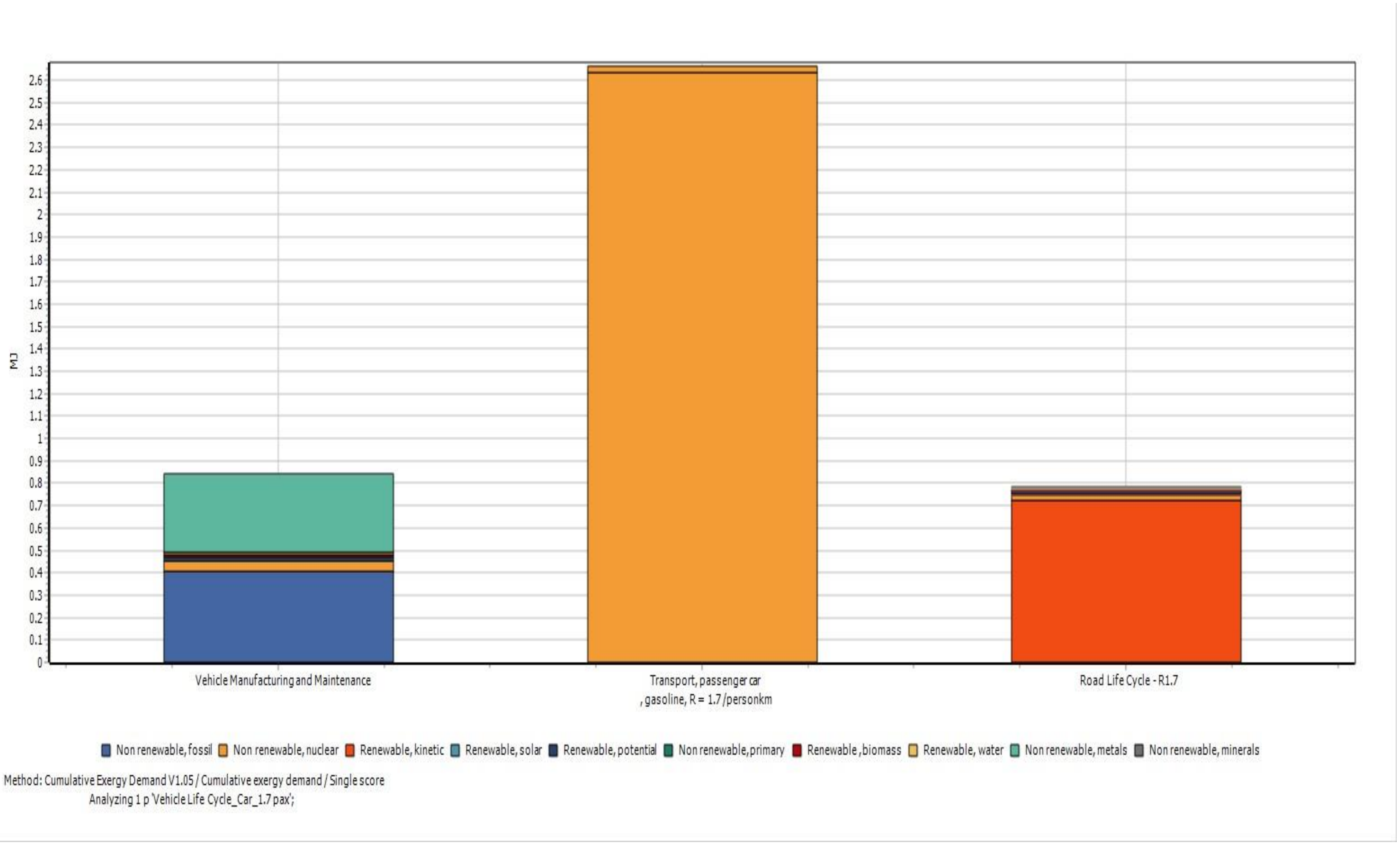


Figure 4-60. Car, Base Case, Single Score, Cumulative Exergy Demand. (Simapro software).

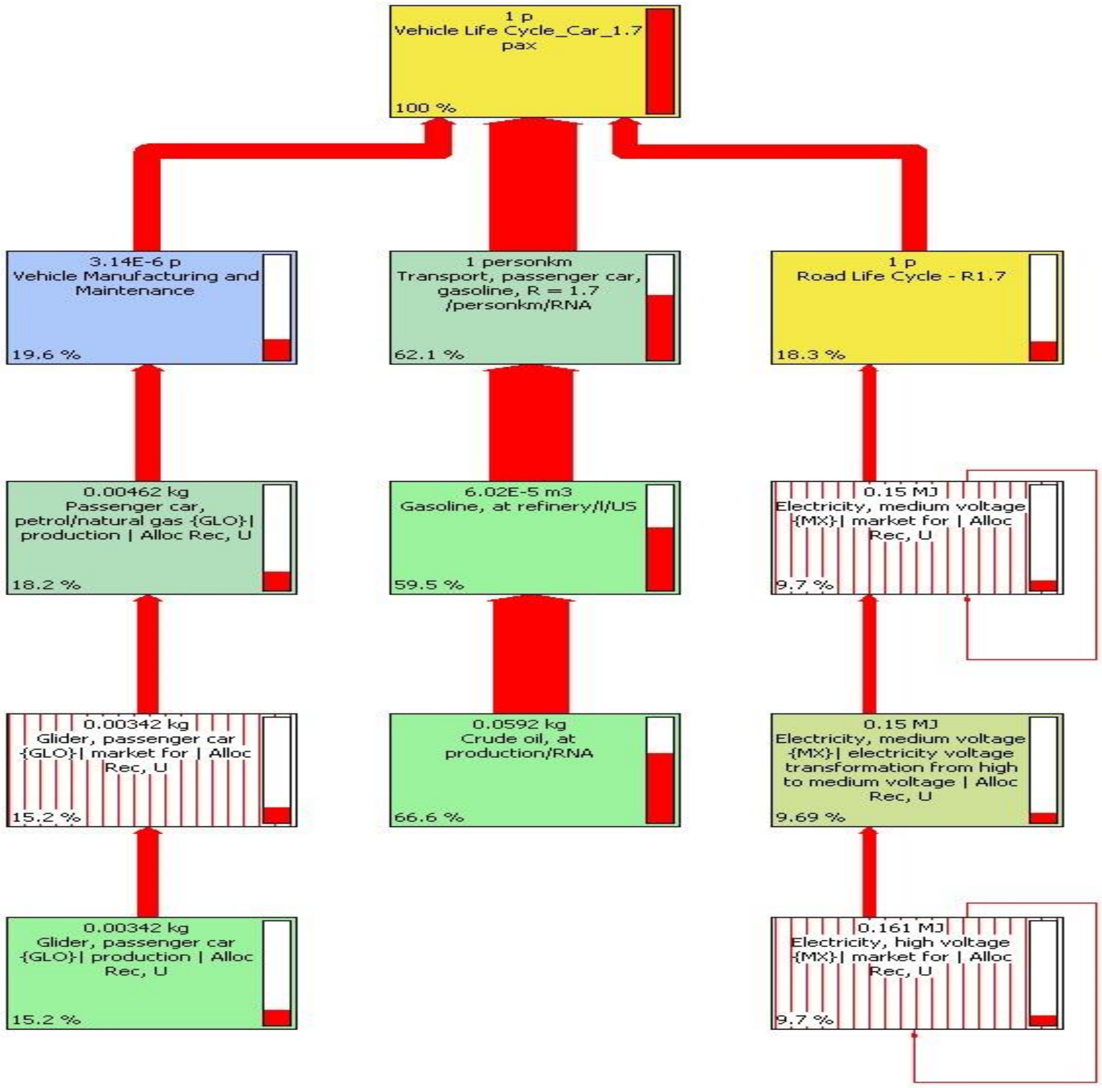


Figure 4-61. Car, Base Case, Network Single Score, Cumulative Exergy Demand. (Simapro software).

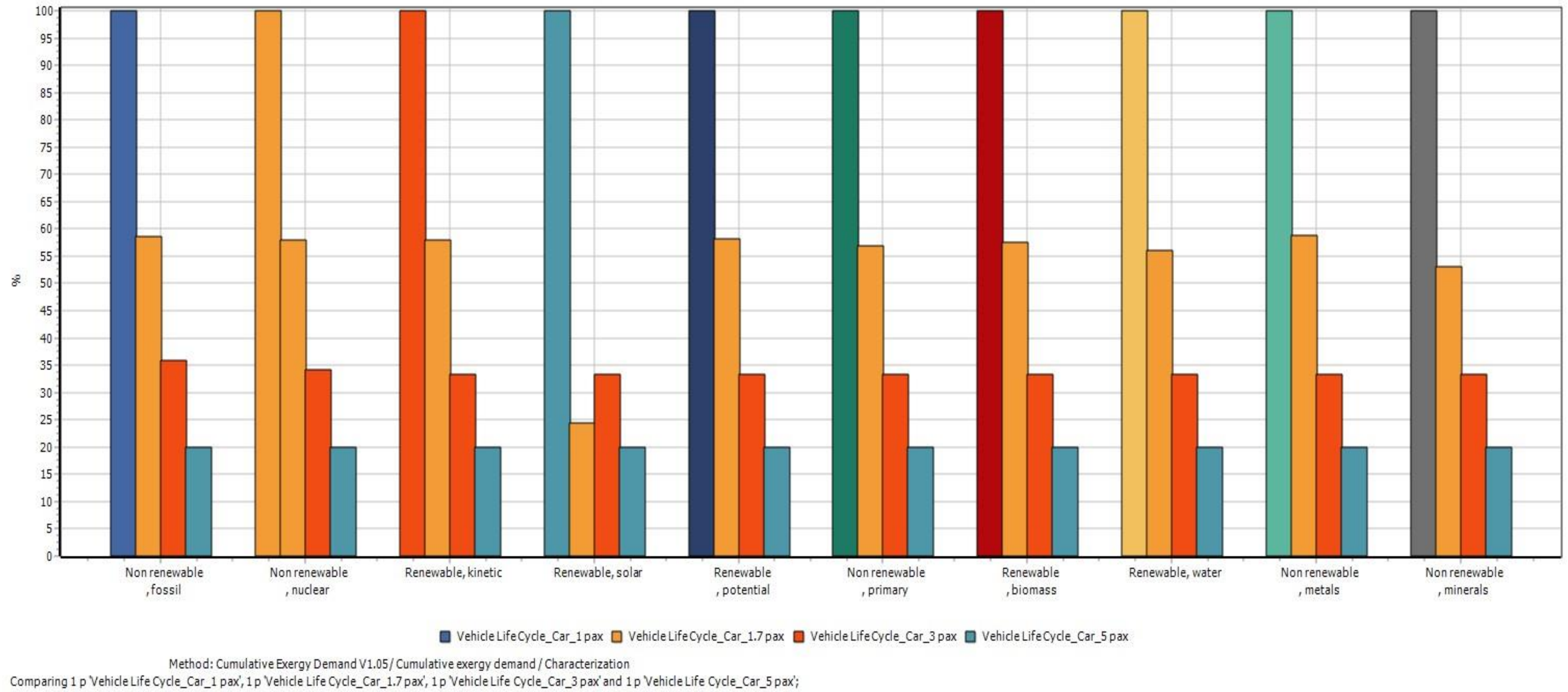


Figure 4-62. Car, Sensitivity Analysis. Comparing Four Different Riderships. Characterization. Cumulative Exergy Demand. (Simapro software).

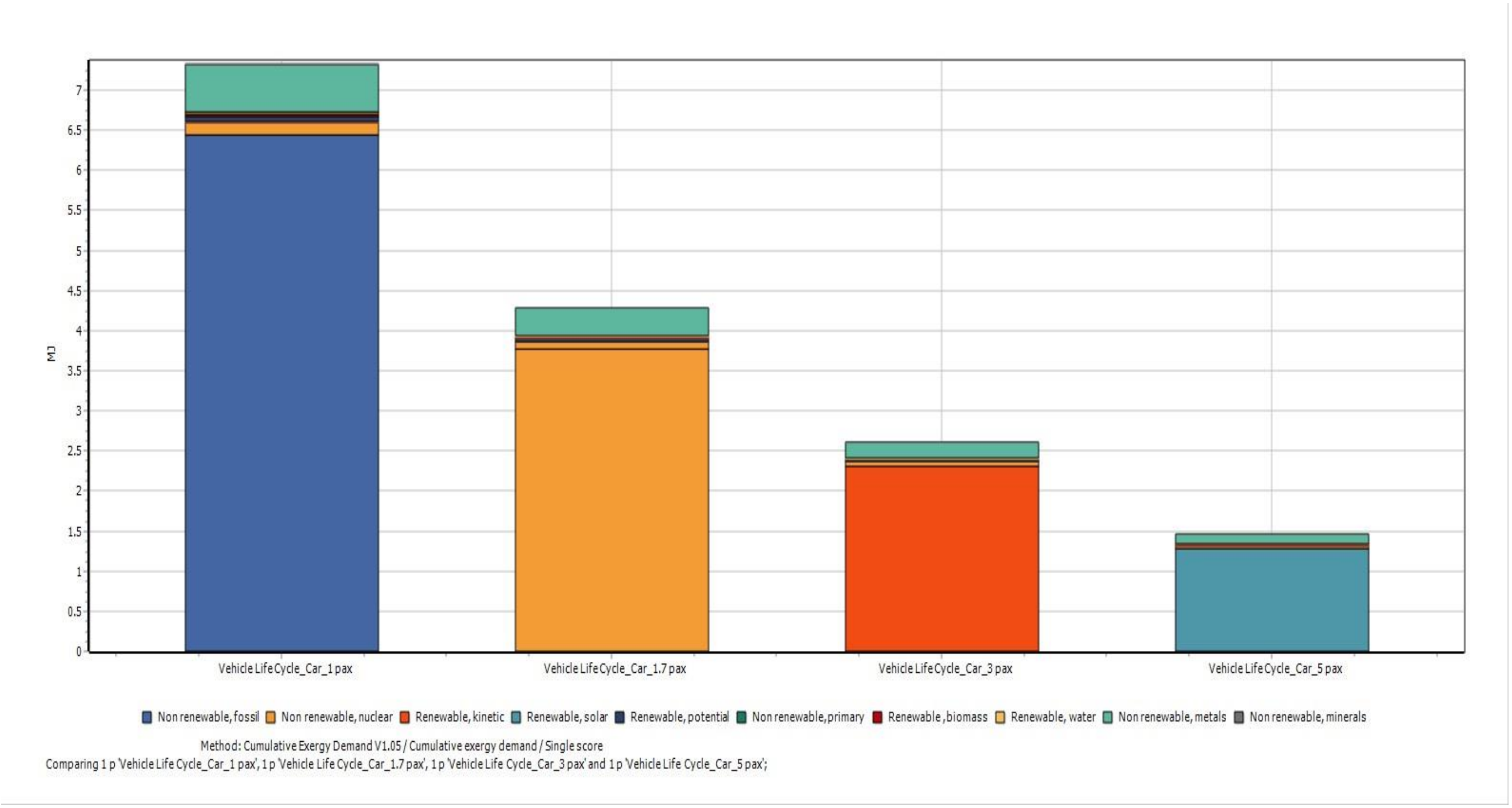
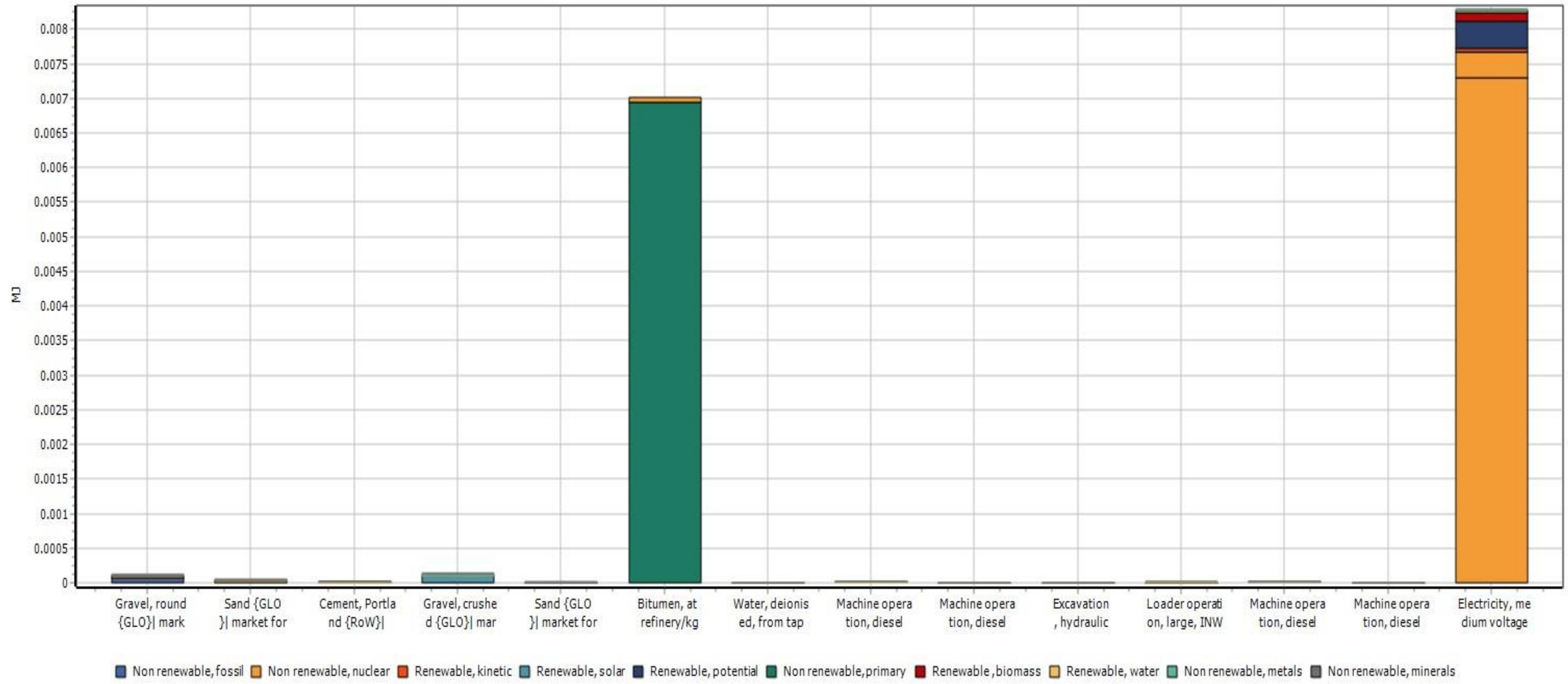


Figure 4-63. Car, Sensitivity Analysis. Comparing Four Different Riderships. Single Score. Cumulative Exergy Demand. (Simapro software).



Method: Cumulative Exergy Demand V1.05 / Cumulative exergy demand / Single score
Analyzing 1 p 'Road Unit Km Construction_Car';

Figure 4-64. Car, Unit Kilometer of Road. Single Score, Cumulative Exergy Demand (Simapro software).

4.5.3 Cumulative Exergy Demand for Subway

As before, a Cumulative Energy Demand analysis was run on the subway system as background to the Cumulative Exergy Demand. Figure 4-65 shows the characterization and Figure 4-66 the single score phase of the Cumulative Energy Demand assessment of the subway. The vehicle’s operation accounts for over 98% of the impact, mostly in the non-renewable, fossil category.

Figure 4-67 shows the results of the characterization phase of the Cumulative Exergy Demand. Other than the expected preponderance of the vehicle’s operation in all categories, one of the notable results in this figure is the important contribution of the railway’s life cycle to the non-renewable, minerals, category. This is probably reading the lifetime effect of the steel used for the tracks, throughout the railway’s life cycle. Figure 4-68 shows the single score of the Cumulative Exergy Demand of the subway, and ratifies that the greatest contribution to the impact comes from the vehicle operation, in the non-renewable, fossil category. Nevertheless, it is also interesting to observe that the second category with the greatest impact is non-renewable, nuclear, followed by the renewable, potential category. This is most probably mirroring the source composition of the Mexican electricity mix, which is mostly fossil fuel-based, but also has a nuclear and hydropower component. This latter composition is the one that is probably being reflected in the renewable, potential, category.

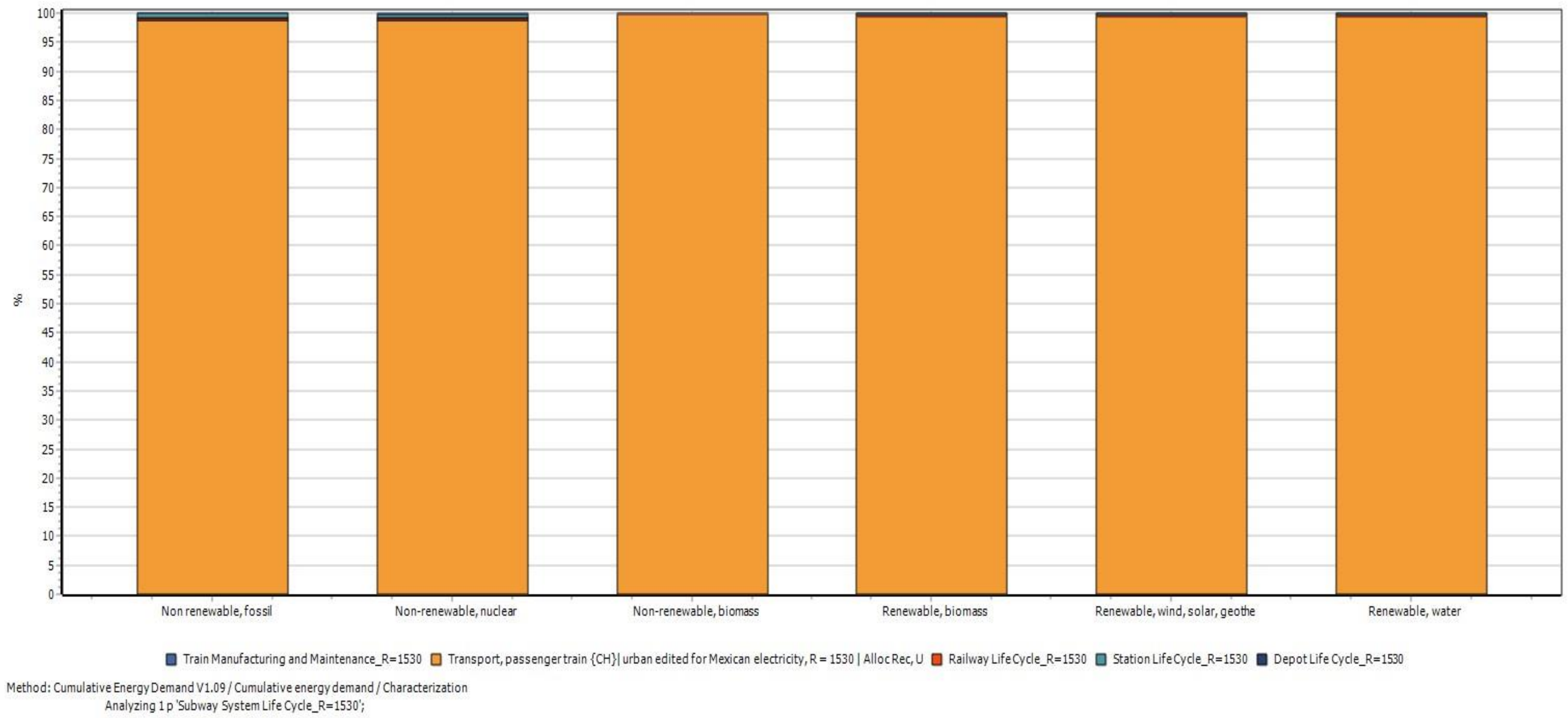


Figure 4-65. Subway, Base Case, Characterization, Cumulative Energy Demand, (Simapro software).

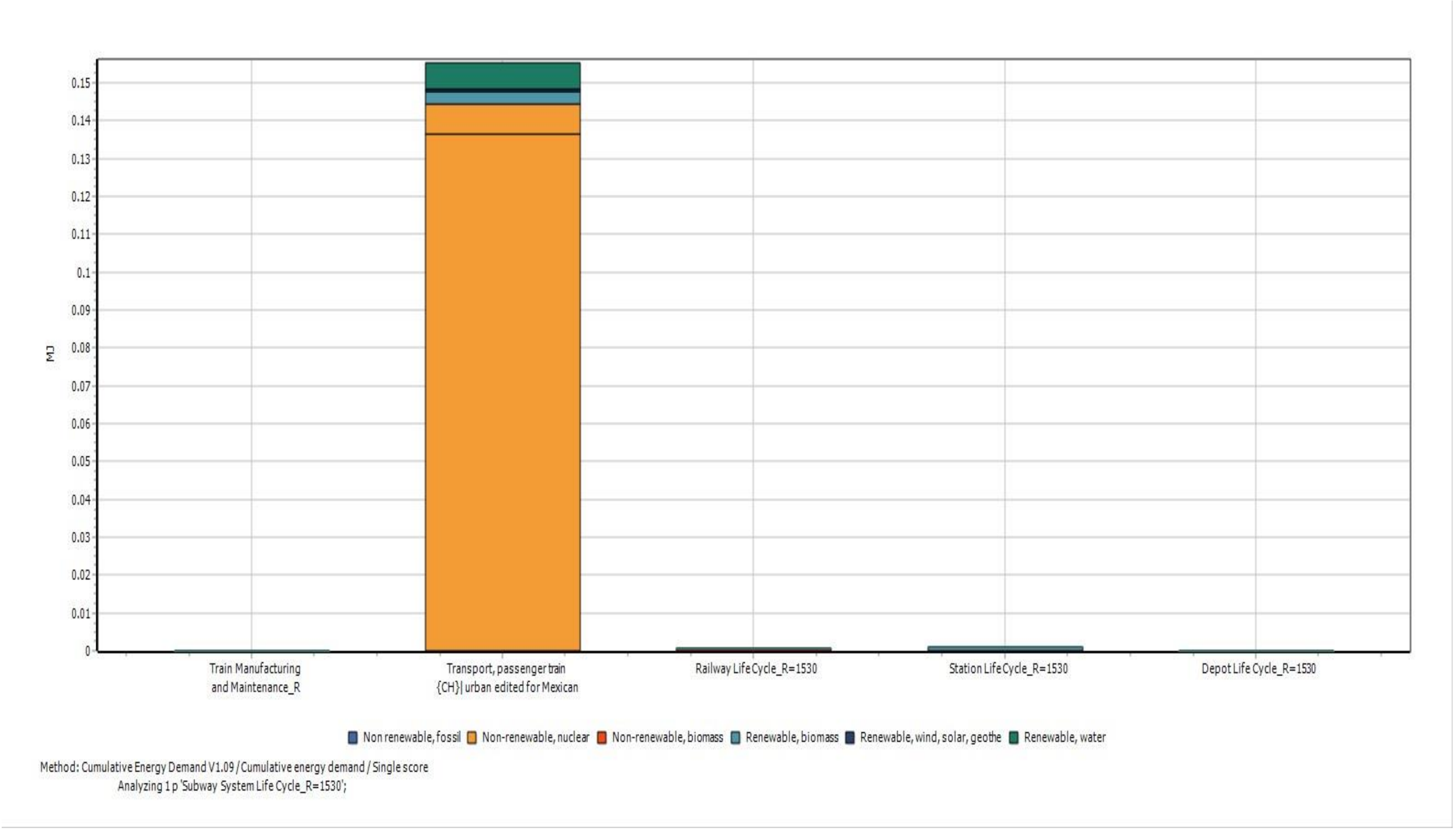


Figure 4-66. Subway, Base Case, Single Score, Cumulative Energy Demand (Simapro software).

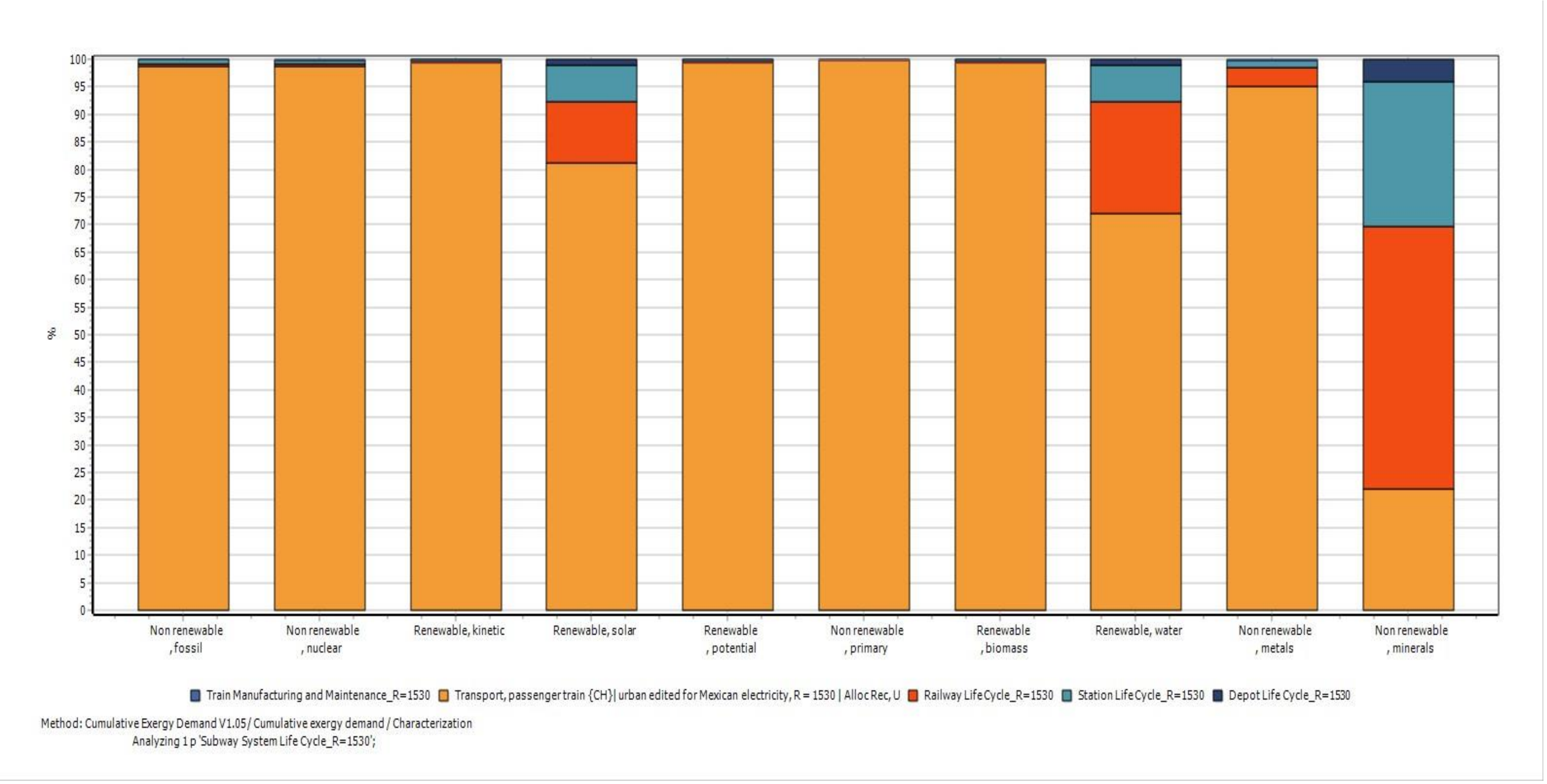


Figure 4-67. Subway, Base Case, Characterization, Cumulative Exergy Demand (Simapro software).

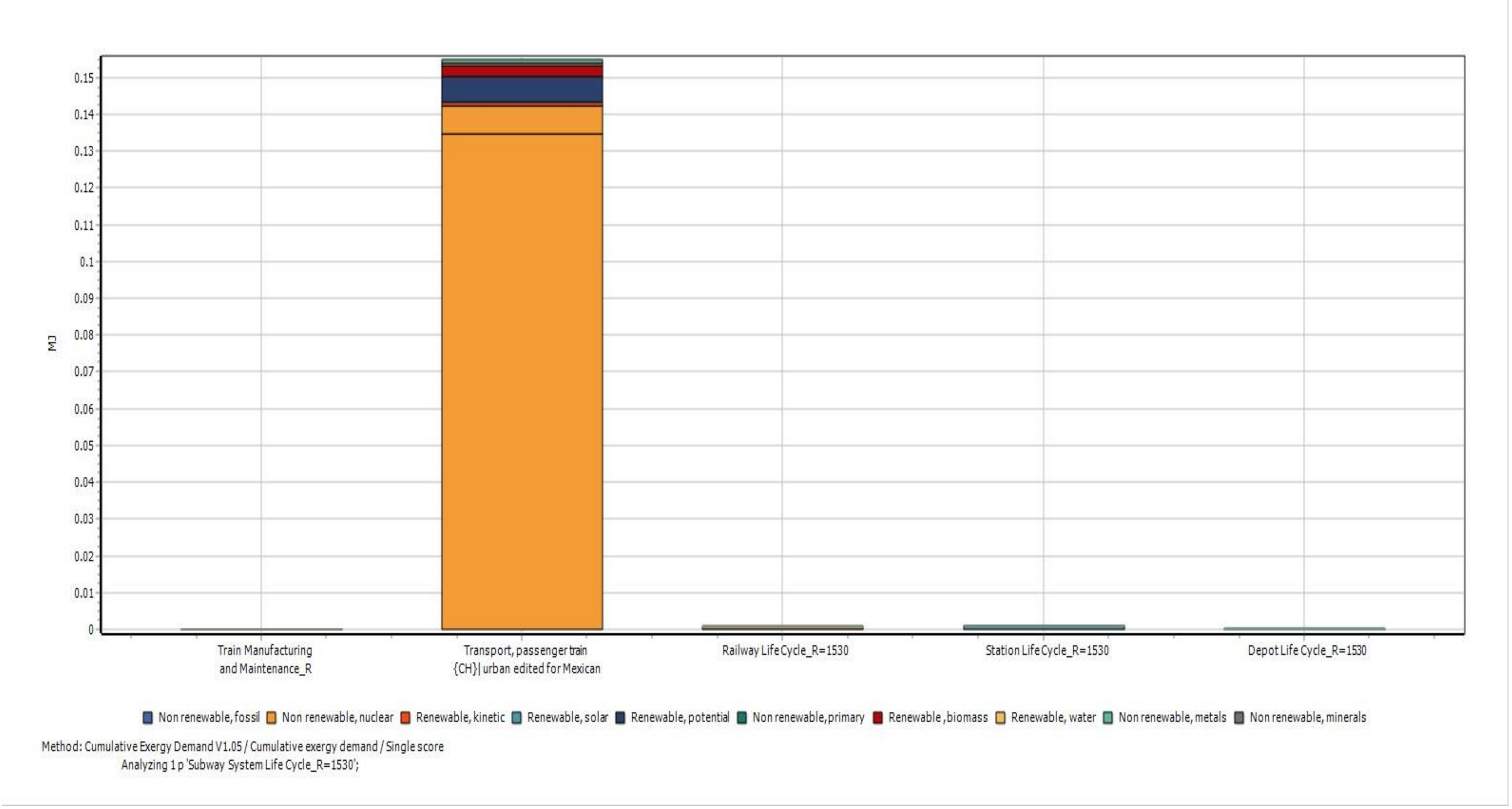


Figure 4-68. Subway, Base Case, Single Score, Cumulative Exergy Demand (Simapro software).

4.6 Results for Research Objective 4 (Conduct Sensitivity Analysis to determine Range of Environmental Impacts)

4.6.1 Sensitivity Analysis for BRT

After obtaining a comprehension of the system's behavior, and as mentioned in Section 3.6.1.1, three different sensitivity parameters were analyzed relative to the base case of the BRT, as summarized in Table 4-18. The first one was ridership, and for this, two different buses, the articulated and the biarticulated model of the Volvo 7300, each with a peak and off-peak ridership, were modeled. Ridership was chosen as a sensitivity parameter because of two main reasons. First, there was interest in knowing how air pollutants and other emissions, and eventually, impacts, might be affected by an increased ridership. In the second place, previous studies, particularly in the *Transmilenio* BRT System of the city of Bogotá, Colombia (Cuéllar et al., 2016) have shown that the BRT system is highly sensitive to variations in ridership, and that varying ridership, from low to high values, creates a range of impacts, when measured in grams of emissions per passenger-kilometer. The two models of the 7300 BRT Volvo bus were chosen because they are the most prevalent models in Line 1. Furthermore, since they are essentially the same bus, only with an increased mass, and the fact that the Articulated bus has a listed capacity of 160 passengers and the Bi-articulated bus holds 240 passengers, it was convenient to include them for ease of modeling.

Table 4-18. Summary of Sensitivity Parameters and Scenarios for BRT.

Sensitivity Scenario	Ridership	Station Lifetime	Vehicle Lifetime
Base Case	160 passengers for Articulated, Peak Bus	25 years	12 years
Different Riderships	160 passengers for Articulated, Peak Bus 90 passengers for Articulated, Off-Peak Bus 240 passengers for Bi-articulated, Peak Bus 144 passengers for Bi-articulated, Off-Peak Bus	25 years	12 years
Increased Station Lifetime	160 passengers for Articulated, Peak Bus	40 years	12 years
Decreased Vehicle Lifetime	160 passengers for Articulated, Peak Bus	25 years	7 years

Figure 4-69 shows the results of the characterization phase, and Figure 4-70 of the single score phase of applying the BEES+ method to each of these four different "products," or buses, each with its respective ridership. It must be noted that the decrease in impact in a per passenger-kilometer basis is strictly linear, and it affects not only the most prominent impact category, the global warming category in all buses, but it also affects all other categories. This is very clear in the linear decrease with increased ridership that is shown in the natural resource depletion, eutrophication, smog and ecotoxicity categories. Another noteworthy observation from Figure 4-70 is that the off-peak biarticulated bus actually has a greater environmental impact than the peak articulated bus. That is, it is the increased number of passengers actually using the buses, and not so much the size of the bus *per se*—which leads to decreased impacts. A further research question, beyond the scope of this study, would be to determine if and at what number of passengers it becomes actually more convenient to dispatch more biarticulated buses than articulated ones from the depot. Since Line 1 of Mexico City's BRT has long ago reached its saturation point, particularly during peak hours, it would be safe to assume that the number of passengers has already exceeded this threshold, and it makes more sense to dispatch biarticulated buses at this time.

The second sensitivity parameter examined for the BRT was the station's lifetime, which as the most significant module of the infrastructure subsystem, was increased to an assumed lifetime of 40 years. This parameter was varied to determine whether an assumed increased lifetime for the infrastructure would be reflected on the system's environmental impact, and if so, by what measure. Figure 4-71 shows the characterization results and Figure 4-72 shows the single score phase results of the BEES+ method applied to the base case bus, but in one case, with the increased 40-year lifetime. The results show that while there was not so much difference in the fuel-dependent impact categories (such as global warming, natural resource depletion, and smog), there was a noticeable difference in the land-use related categories. Namely, the greatest difference observed was in the water intake and the habitat alteration impact categories, which confirms that the method was correctly identifying the source and the eventual impact of the altered sensitivity parameters. Additionally, it must be pointed out that altering this particular parameter, the station's lifetime, actually creates a non-linear model, in that the results of this sensitivity parameter are non-linear, affecting some impact categories, but not others, and not in the same proportion. On the other hand, it is very likely that Simapro is reading the construction of the station as taking place on a new site, and is thus assigning this impact in land use to the BRT system, under that assumption. However, since these stations were built on already existing medians, and as was mentioned in Chapter 3 previously as well, the Avenida Insurgentes Avenue in Mexico City along which the BRT runs, has been in existence since the nineteenth century, so there was no real alteration in habitat by the construction of the BRT stations. Therefore, land use impacts were not considered as significant for this study as these numbers suggest.

The third sensitivity parameter analyzed for the BRT was the vehicle’s lifetime, which was reduced from the base case’s 12 years to 7 years, a 42% reduction. This sensitivity parameter was altered to see if there was any significant impact associated with a decreased - or alternatively, an increased - lifetime for the vehicle, and how this might affect the environmental impacts in a per passenger-kilometer basis. Figure 4-73 shows the results at the characterization phase and Figure 4-74 shows the single score results. As expected, with a shorter lifetime the impacts are increased, or said another way, impacts are generally decreased with increased lifetime. Examination of these results shows that, once again, while the fuel-dependent impact categories are virtually unchanged, of affected very little in their lifetime impact, the human health categories (both cancer and noncancer), and the ecotoxicity, habitat alteration and water intake categories are all noticeably affected. However, in none of these cases a 42% reduction of the vehicle’s lifetimes translates into a corresponding 42% decrease in impact. On the contrary, as the single score results show, altering the vehicle’s lifetime, while resulting in a perceivable change, does not have as dramatic an effect upon the system as the ridership parameter did.

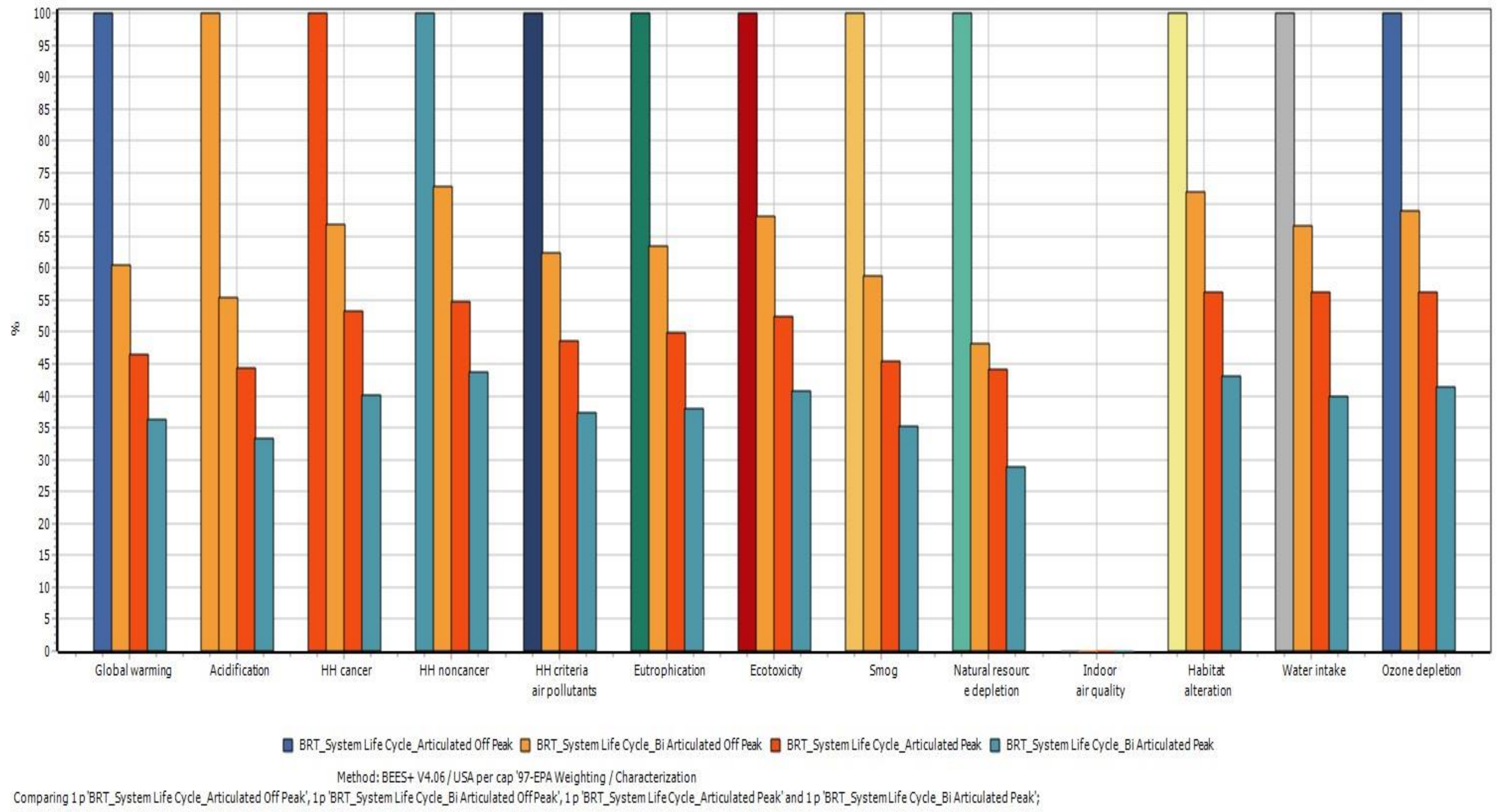


Figure 4-69. BRT, Sensitivity Analysis, Four Different Riderships. Characterization, BEES+ (Simapro software).

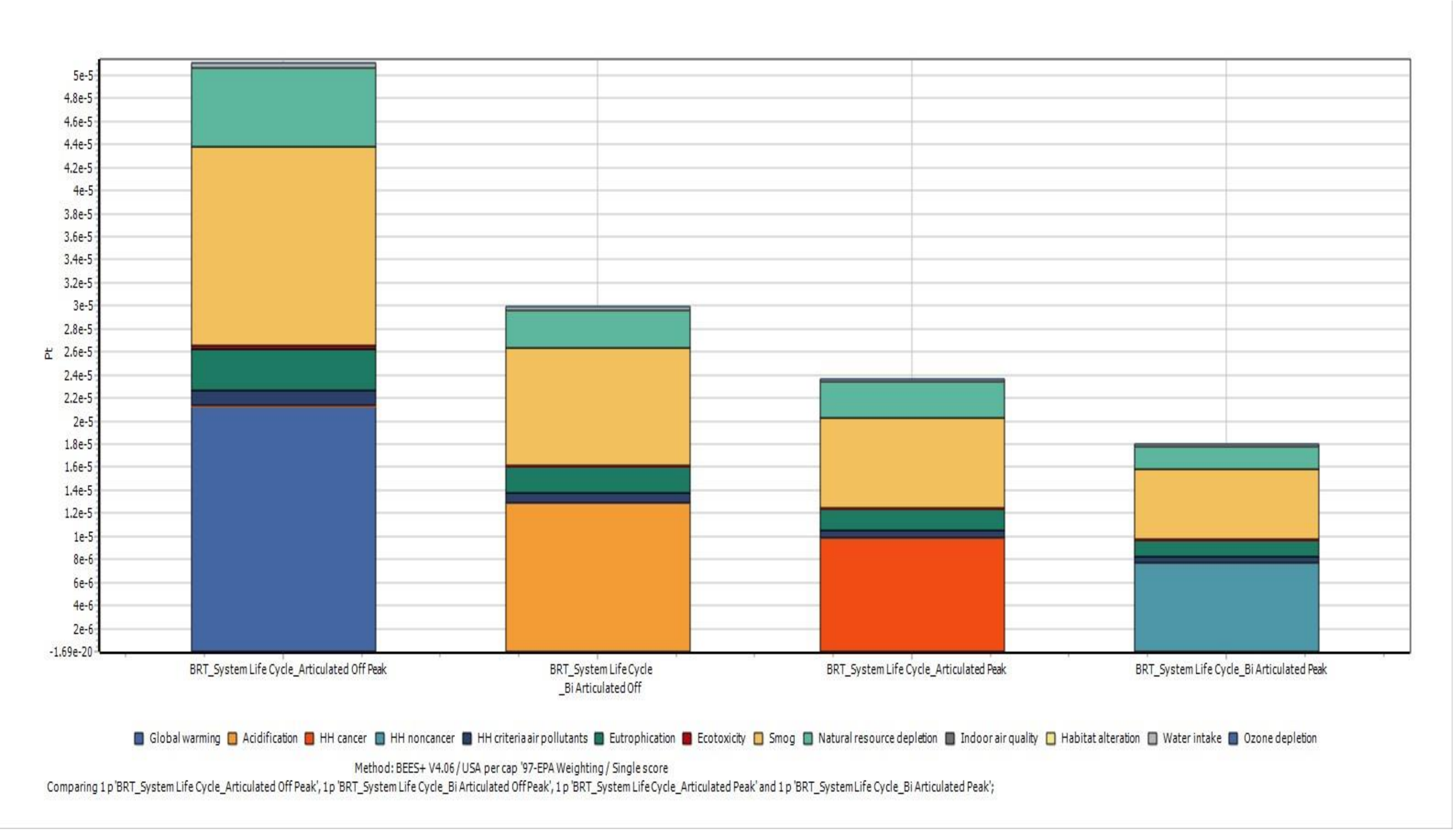
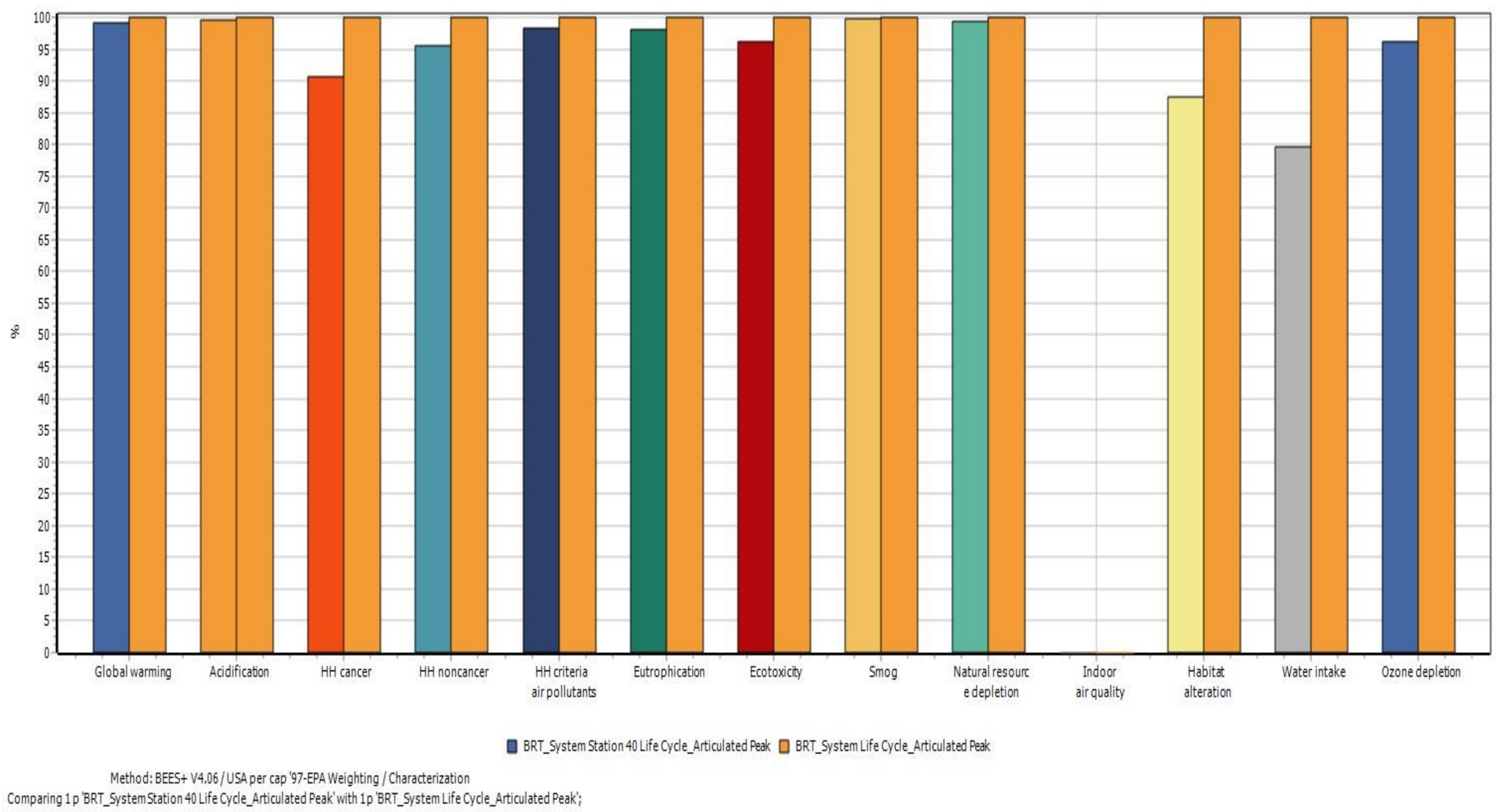


Figure 4-70. BRT, Sensitivity Analysis, Four Different Riderships. Single Score., BEES+ (Simapro software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Characterization
Comparing 1 p 'BRT_System Station 40 Life Cycle_Articulated Peak' with 1 p 'BRT_System Life Cycle_Articulated Peak';

Figure 4-71. BRT, Sensitivity Analysis, Different Station Lifetimes. Characterization, BEES+ (Simapro software).

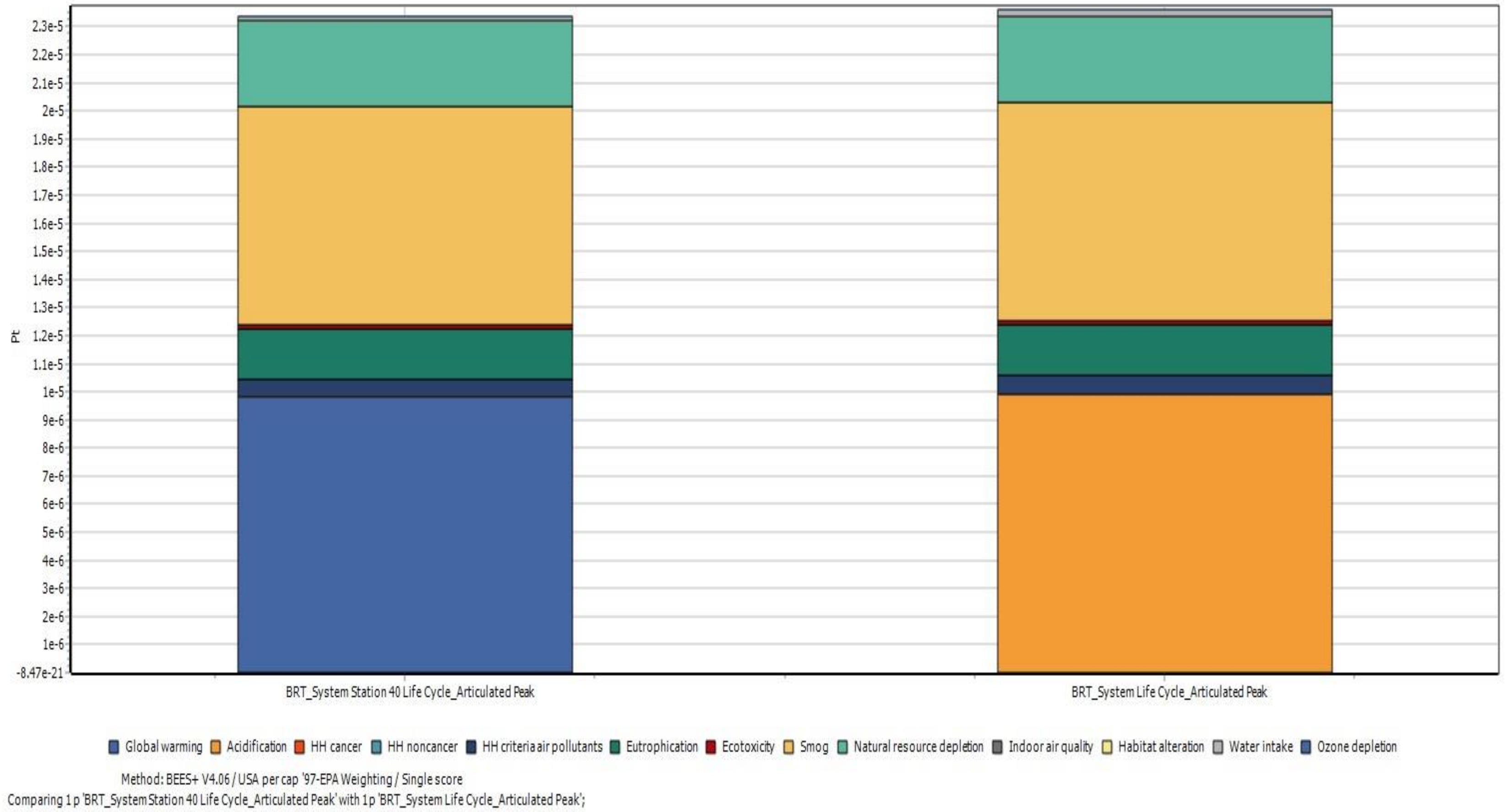


Figure 4-72. BRT, Sensitivity Analysis, Different Station Lifetimes. Single Score, BEES+ (Simapro software).

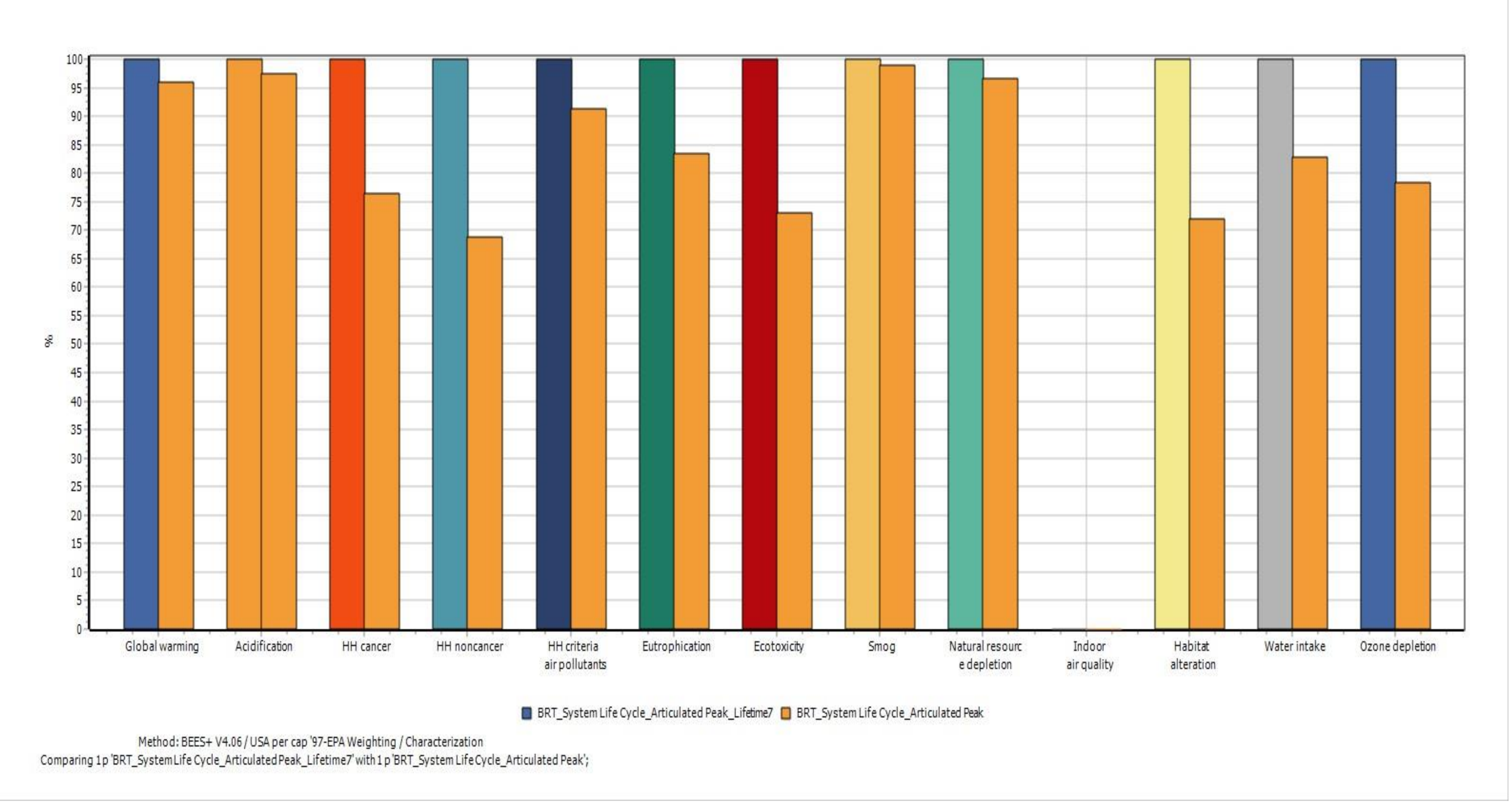
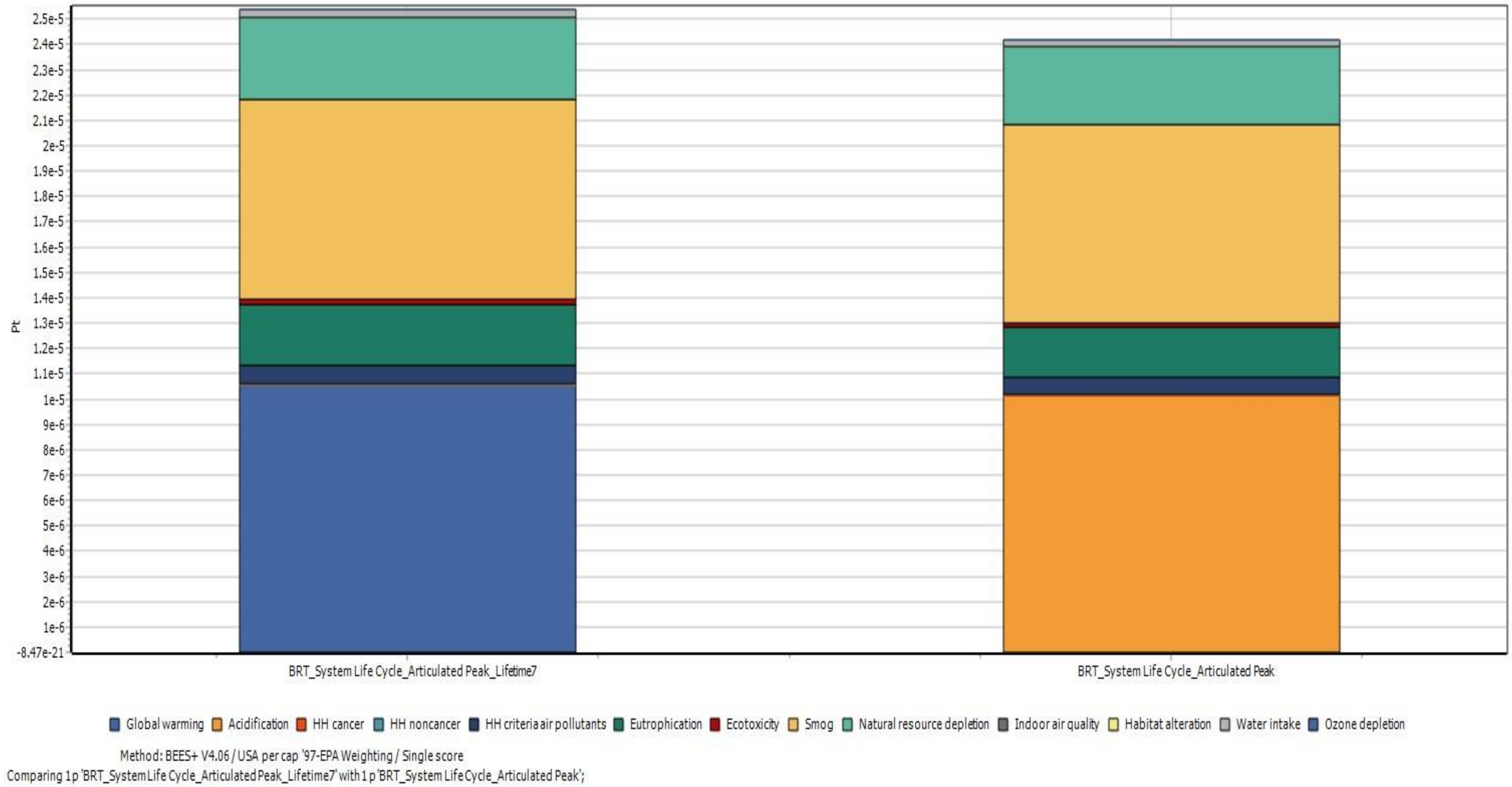


Figure 4-73. BRT, Sensitivity Analysis, Different Vehicle Lifetimes. Characterization, BEES+ (Simapro software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Single score
Comparing 1 p 'BRT_System Life Cycle_Articulated Peak_Lifetime7' with 1 p 'BRT_System Life Cycle_Articulated Peak';

Figure 4-74. BRT, Sensitivity Analysis, Different Vehicle Lifetimes. Single Score, BEES+ (Simapro software).

4.6.2 Sensitivity Analysis for Car

As mentioned in Section 3.6.1.2, three different sensitivity parameters were analyzed relative to the base case of the car. The first one was ridership, and given that the absolute minimum possible ridership for a car is 1 passenger, and the maximum, according to technical specifications from the manufacturer, is 5 persons, four riderships were modeled with the intention of creating a range of possible impacts for the car, from the lowest to the maximum, including the average ridership for the base case. Riderships were then set for 1, 1.7, 3 and 5 passengers. Table 4-19 shows the inventory results of the lifecycle for these four cars, in terms of greenhouse gases and criteria air pollutants. These results are presented in kilograms, the default unit; conceptualizing these numbers in terms of the more familiar g/passenger-kilometer would probably be helpful. Thus, it can be seen that for 1 passenger the lifecycle carbon dioxide is 386 g of CO_2/passenger-kilometer; for the average ridership of 1.7 passengers, it is 220.84 g of CO_2/passenger-kilometer; and for 5 passengers it decreases to 77.37 g of CO_2/passenger-kilometer. Similarly, the remaining GHG and CAPs can be visualized.

Table 4-19. Inventory Results for Greenhouse Gases and Criteria Air Pollutants. Sensitivity Analysis, Four Different Riderships, Car.

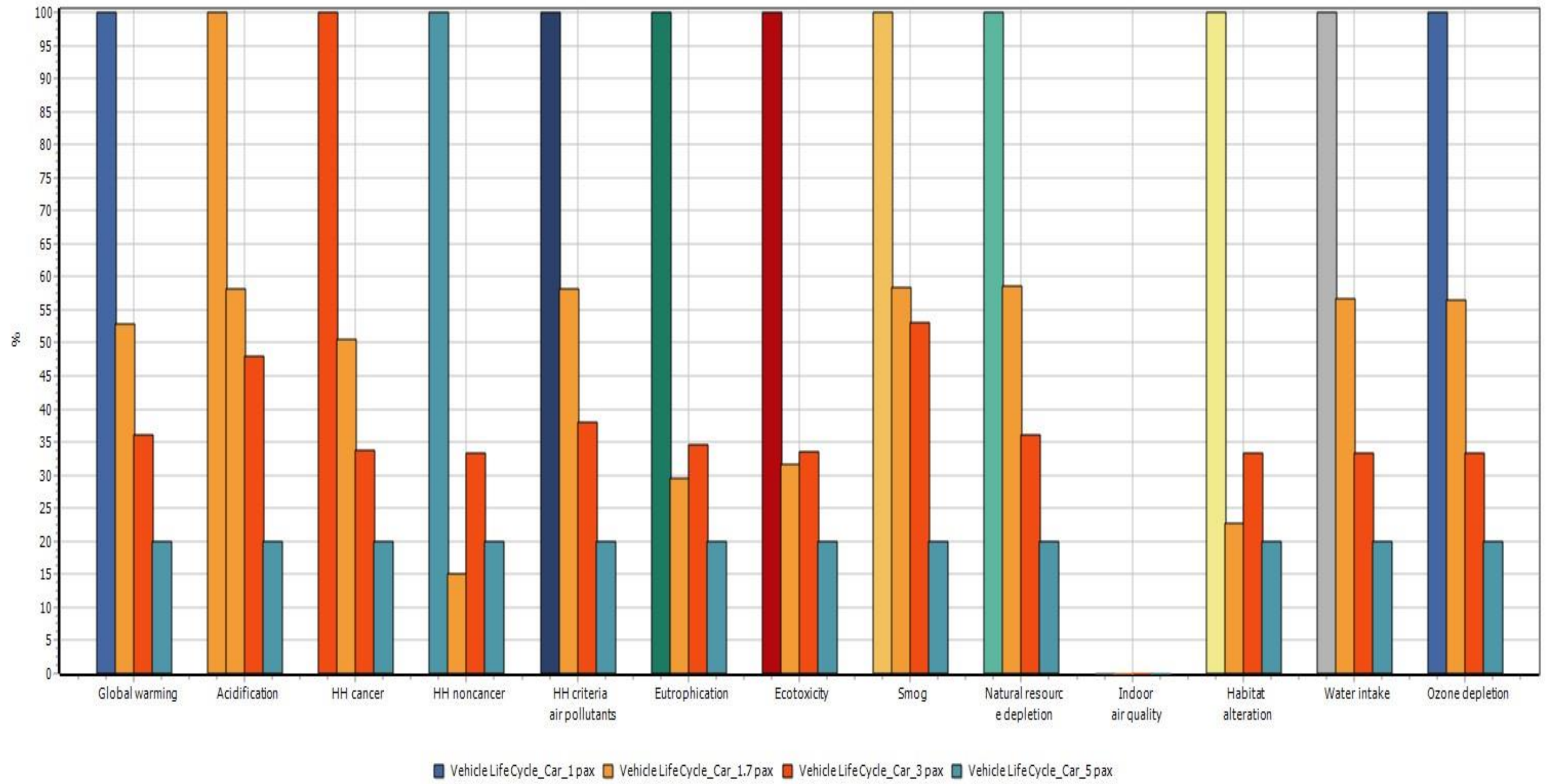
Substance	Unit	Vehicle Life Cycle_Car_1 pax	Vehicle Life Cycle_Car_1.7 pax	Vehicle Life Cycle_Car_3 pax	Vehicle Life Cycle_Car_5 pax
Carbon dioxide, fossil	kg	0.387	0.221	0.141	0.0774
Carbon monoxide, fossil	kg	0.00568	0.00334	0.00197	0.00114
Dinitrogen monoxide	kg	1.71E-05	9.32E-06	5.94E-06	3.42E-06
Hydrocarbons, unspecified	kg	0.000344	0.000202	0.000115	6.88E-05
Lead	kg	1.65E-07	9.60E-08	5.49E-08	3.29E-08
Methane	kg	0.000441	0.000260	0.000161	8.82E-05
Nitrogen dioxide	kg	5.08E-05	2.99E-05	1.69E-05	1.02E-05
Nitrogen oxides	kg	0.00116	0.000676	0.000683	0.000232
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	0.000314	0.000184	0.000111	6.29E-05
Ozone	kg	4.88E-07	2.84E-07	1.63E-07	9.75E-08
Particulates, < 10 µm	kg	2.04E-05	1.20E-05	6.81E-06	4.09E-06
Particulates, < 2.5 µm	kg	0.000159	9.22E-05	5.30E-05	3.18E-05
Sulfur dioxide	kg	0.000592	0.000344	0.000203	0.000118
VOC, volatile organic compounds	kg	0.000369	0.000217	0.000134	7.38E-05

Figure 4-75 shows the characterization results, and Figure 4-76 presents the single score of the BEES+ method applied to the aforementioned 4 riderships. Confirming the inventory, a linear decreasing trend can be observed with increased ridership. Furthermore, this tendency is observed across almost all impact categories, again in a linear fashion. The ecotoxicity, eutrophication and habitat alteration categories present a slight variation from a perfectly linear trend, in that the car with ridership of three persons appears to have a greater impact than the 1.7 passenger car, at the characterization phase. Nevertheless, this result is not replicated at the single score phase, which ratifies a linear trend, across all categories.

The second sensitivity parameter analyzed for the car was the vehicle's lifetime, which was reduced from the base case's 15 years to 10 years. While ten years is typically too short a lifespan for a car in Mexico City, it is indeed closer to the average time it will be used by its first owner (INEGI e, 2016). Figure 4-77 shows the characterization phase and Figure 4-78 shows the single score phase of decreasing the vehicle's lifetime to 10 years, assessed by the BEES+ method. It can be seen that in this case, decreasing the car's lifetime by 33% does show a noticeable increase in impacts in all categories, and while the single score comparison does not show a 33% increase for the less used 10-year car, it does present a significant increase, relative to the base case's 15 years of age. Furthermore, it is also a linear trend in all impact categories.

The third sensitivity parameter analyzed for the car was the road's lifetime, which was increased for the flexible pavement's top layers (the sand for the paver base and the asphalt for the wearing course) from 10 years to 15 years. This parameter was altered not because it was considered uncertain – in fact, given the stress placed upon the flexible pavement at this location, it is quite certain that it will have to be resurfaced at least once, if not more frequently, every ten years—but due to an interest in determining how a less constant resurfacing or replacement of the flexible pavement might decrease environmental impacts. Figure 4-79 shows the characterization results and Figure 4-80 shows the single score results of this sensitivity analysis. Since only the pavement's top layers were altered in this run, the results show a minimal effect at the characterization phase. Moreover, this effect appears constrained to the natural resource depletion impact category. This minimal effect is then reflected at the single score phase (Figure 4-80). In spite of the single score being slightly lower for the increased road lifetime case ("Road15"), it can be seen that both the base case and the increased road lifetime case show a virtually identical result.

Summarizing the results for the sensitivity analysis for this LCA, the car system is highly sensitive to ridership, with an increased ridership leading to a linearly decreased inventory and impact. The car system is also sensitive to alteration in the vehicle's lifetime, although not as strongly and not as linearly as was true for the ridership. Finally, altering the road's lifetime does not appear to have a significant impact on the lifecycle's inventory nor on the different impact categories.



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Characterization
Comparing 1 p 'Vehicle Life Cycle_Car_1 pax', 1 p 'Vehicle Life Cycle_Car_1.7 pax', 1 p 'Vehicle Life Cycle_Car_3 pax' and 1 p 'Vehicle Life Cycle_Car_5 pax';

Figure 4-75. Car, Sensitivity Analysis, Four Different Riderships. Characterization, BEES+ (Simapro software).

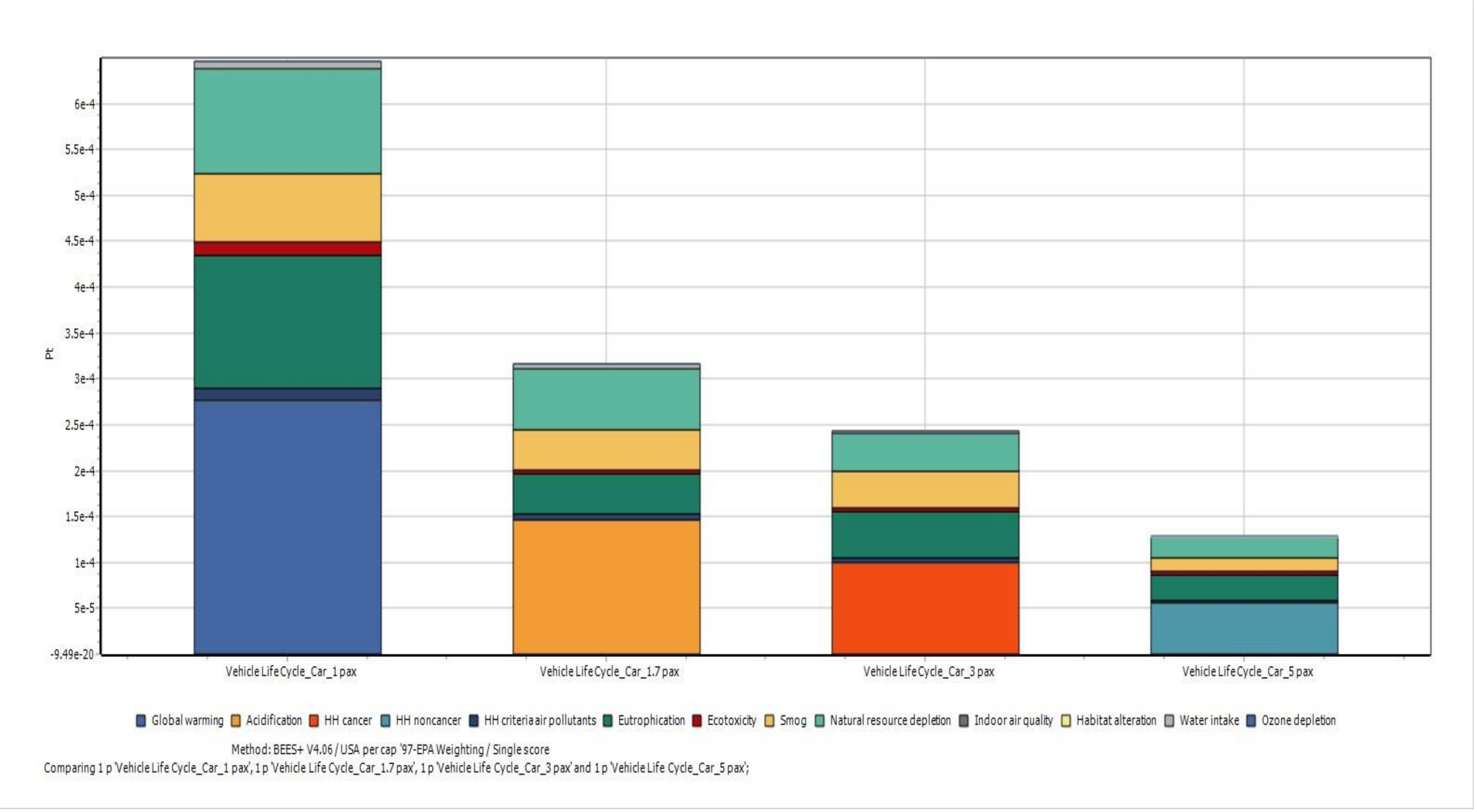


Figure 4-76. Car, Sensitivity Analysis, Four Different Riderships. Single Score, BEES+ (Simapro software).

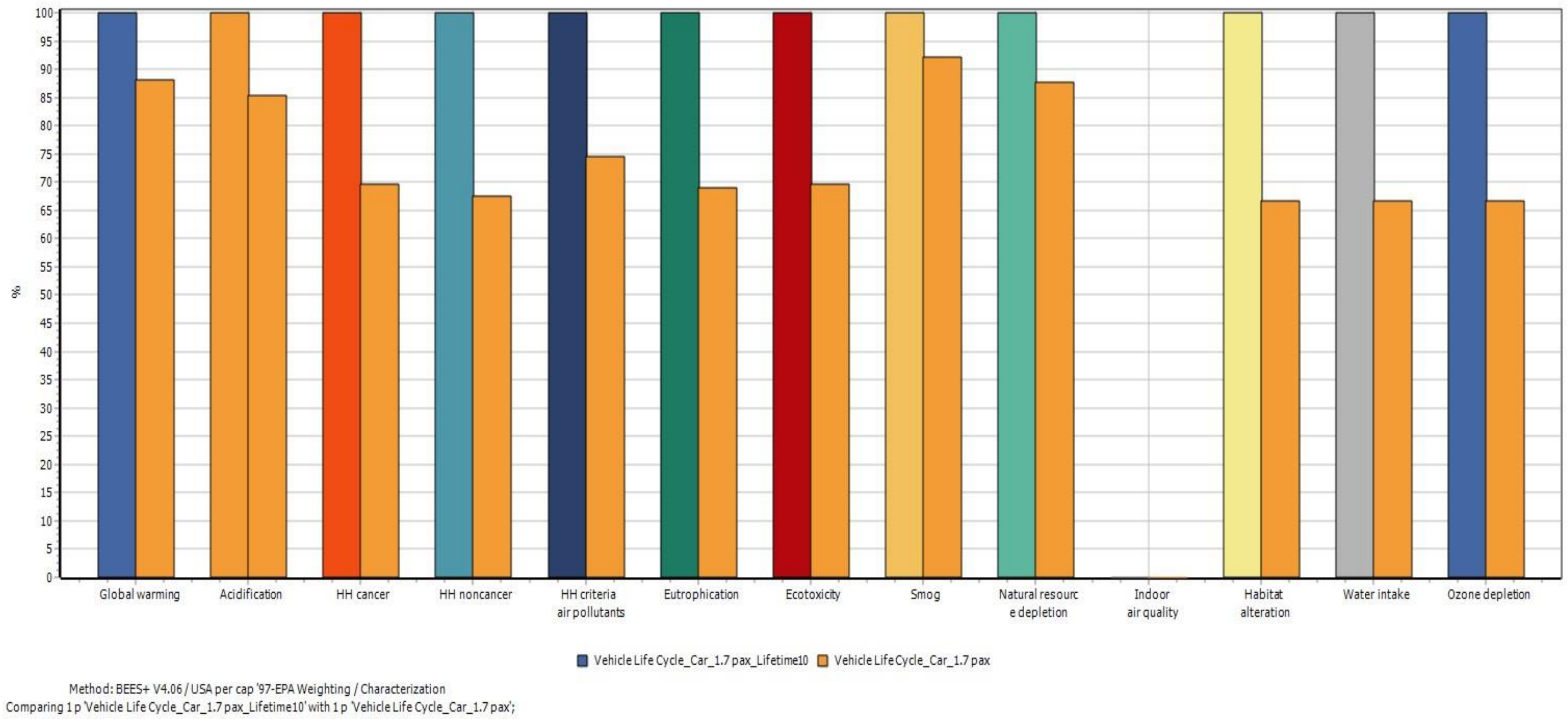
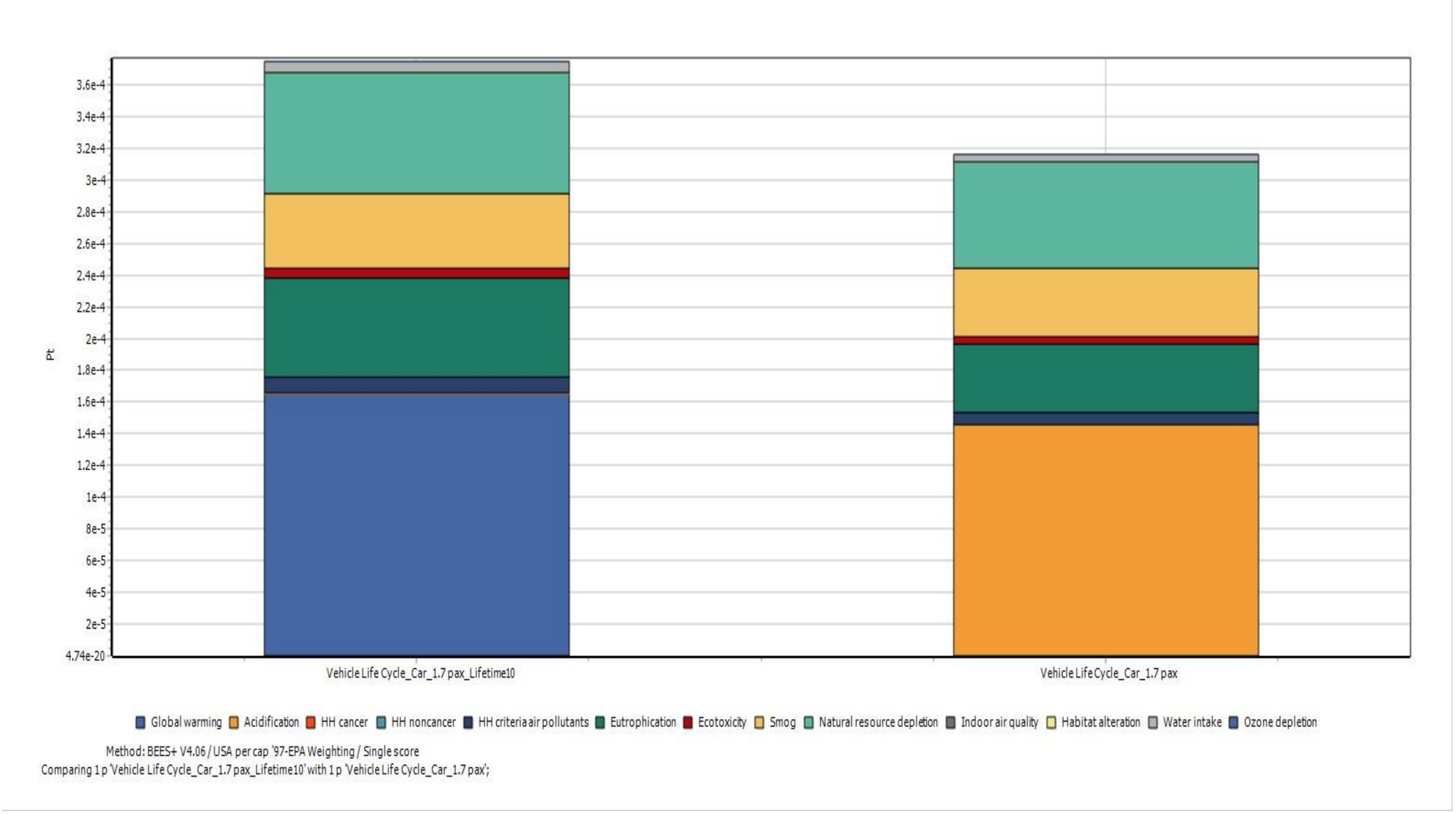


Figure 4-77. Car, Sensitivity Analysis, Different Vehicle Lifetimes. Characterization, BEES+ (Simapro software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Single score
Comparing 1 p 'Vehicle Life Cycle_Car_1.7 pax_Lifetime10' with 1 p 'Vehicle Life Cycle_Car_1.7 pax';

Figure 4-78. Car, Sensitivity Analysis, Different Vehicle Lifetimes. Single Score, BEES+ (Simapro software).

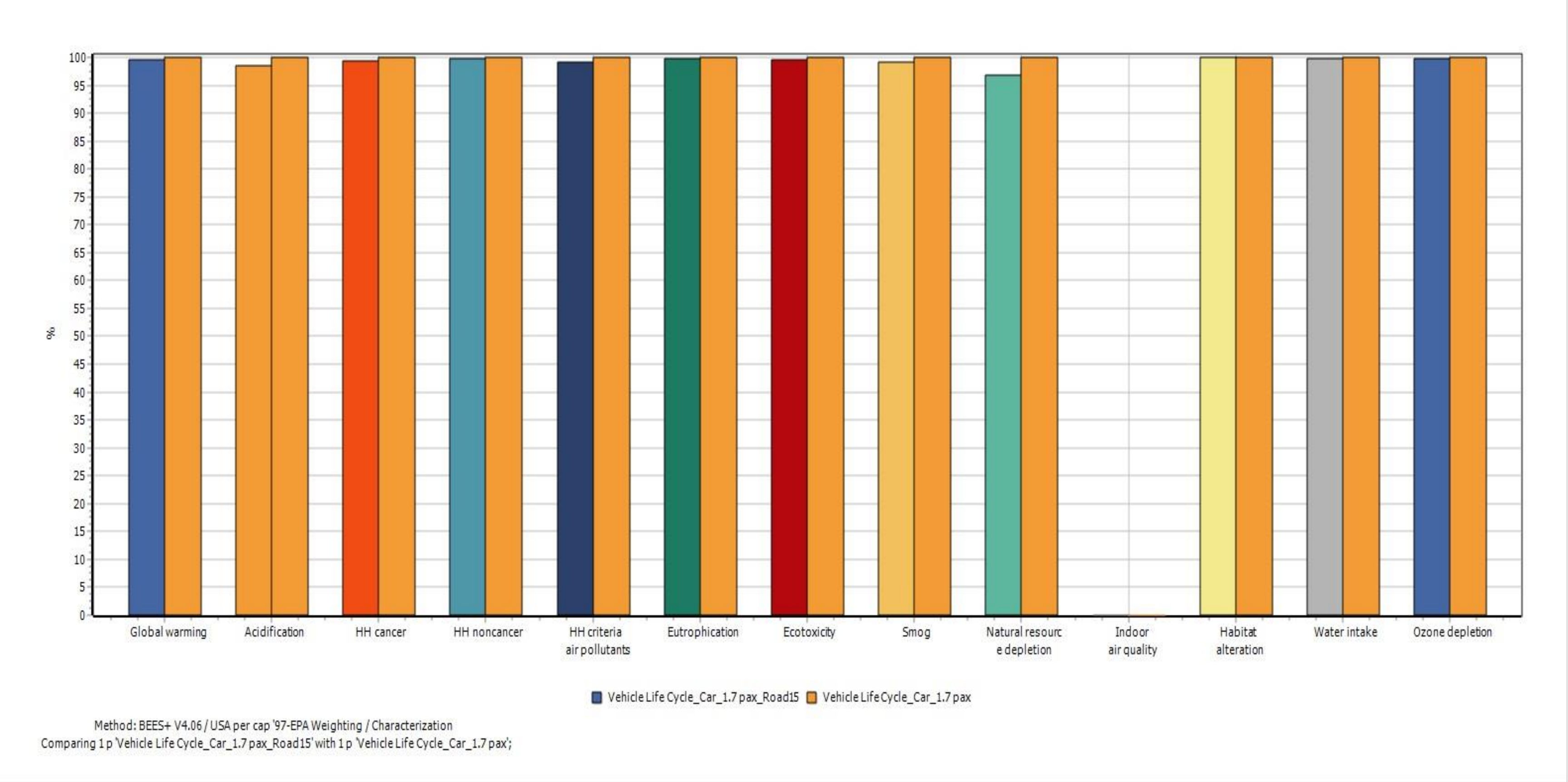


Figure 4-79. Car, Sensitivity Analysis, Different Road Lifetimes. Characterization, BEES+ (Simapro software).

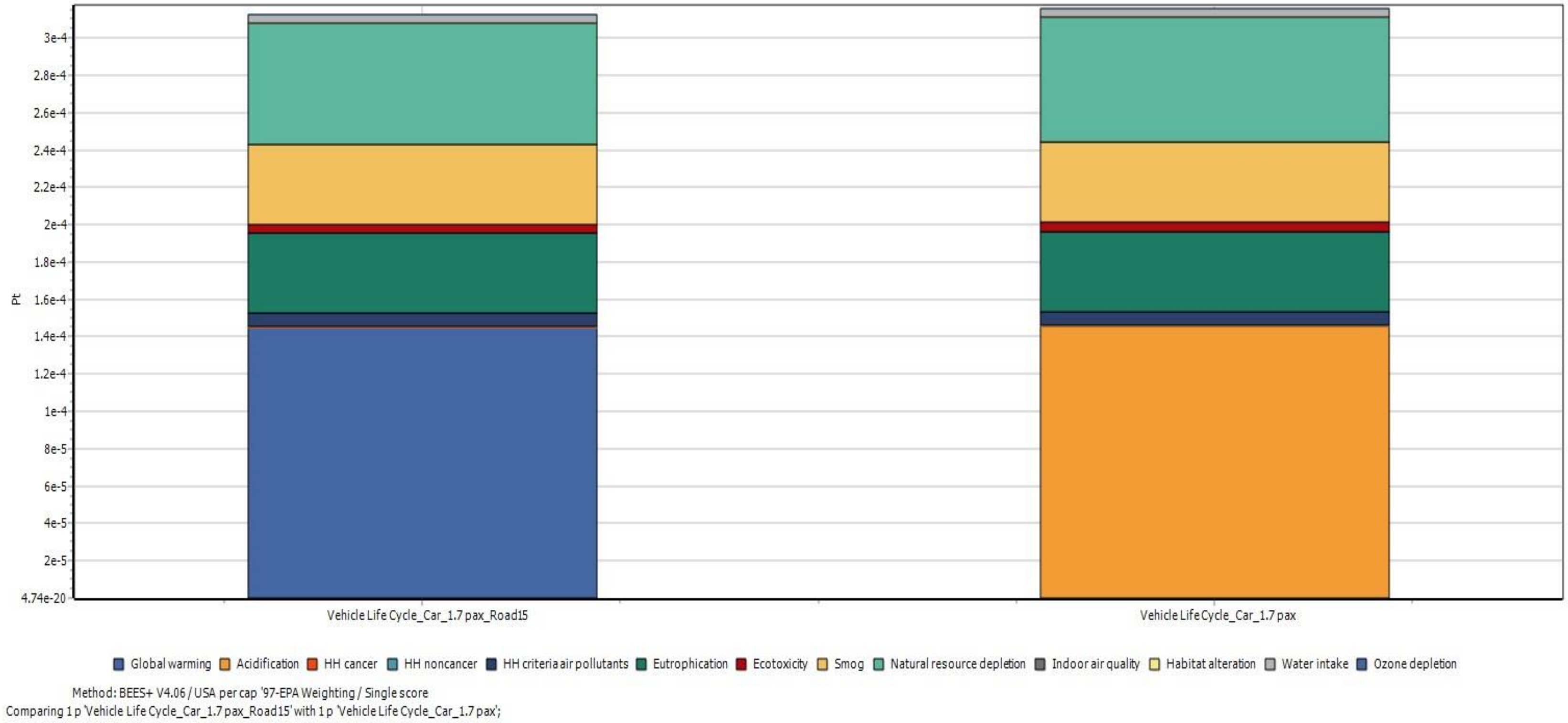


Figure 4-80. Car, Sensitivity Analysis, Different Road Lifetimes. Single Score, BEES+ (Simapro software).

4.6.3 Sensitivity Analysis for Subway

As mentioned in Section 3.6.1.3, three different variables were chosen for analysis for the subway. Ridership was the first of these sensitivity parameters. The listed capacity of the subway train is 1,530 passengers, which was set as the base case's ridership. Additionally, from the answer to the public information request filed with the STC-Metro's transit agency, the off-peak ridership was set as 918 passengers, and the maximum, peak capacity was set at 50% overflow, or 2,295 passengers per train. Moreover, an extremely unlikely, low ridership was set at 306 passengers, in order to provide a range of possible impacts. This low ridership figure was chosen because in one of the STC-Metro's webpages, a "ridership" figure of 34 passengers/train was quoted. Given the impossibility of this figure, it was decided that this was probably a typographical error, and that it should have said 34 passengers per car, and not 34 passengers per train. Given that a Line 3 subway train has 9 cars, if this figure were to be correct, the absolute minimum ridership for a train was estimated as 9 * 34 = 306 passengers. Although unlikely, this ridership was nevertheless modeled. Figure 4-81 shows the characterization results and Figure 4-82 shows the single score results of this ridership sensitivity analysis for the subway system. A linear relationship of decreased impacts, across all impact categories, with an increased ridership can be observed. Furthermore, Table 4-20 shows the inventory results for GHG and CAPs for each one of the riderships modeled for the subway. Since the results are in the default units of kilograms, conversion to grams of pollutant/passenger-kilometer may be useful to give these results their proper dimension. Thus, it can be seen that for the very low ridership of 306 passengers, 39.6 g of CO_2/passenger/kilometer were generated; 14.3 g of CO_2/passenger-kilometer for the ridership of 918 passengers; 9.24 g of CO_2/passenger-kilometer for the base case of 1, 530 passengers and 6.71 g of CO_2/passenger-kilometer for the overflow ridership of 2,295 passengers. These numbers and all other results in Table 4-20 ratify the linear trend of decreasing air pollutants with increased ridership, and as before, also in all categories. Moreover, Table 4-21 once again confirms this linear trend, in this case for the impact categories, of decreased impacts with increased ridership.

A sensitivity analysis was also done for the electricity mix, changing the Mexican electricity mix for the average United States' electricity mix. Figure 4-83 shows the results at the characterization phase and Figure 4-84 shows the results of the single score phase of the BEES+ method, comparing both electricity mixes. Interestingly, although the Mexican electricity mix has a greater characterization impact in the acidification, smog, natural resource depletion and ozone depletion categories than the United States' mix, when the single score phase is reached, it is the United States' mix the one that has the greatest impact. Table 4-22 shows the results, in each of the impact categories, for both the base case and the United States' electricity mix. To confirm or deny this result, further analyses, now using the Cumulative Energy Demand and the Cumulative Exergy Demand methods were employed in this sensitivity case. Figure 4-85 shows the characterization results and Figure 4-86 shows the single score phase results of the Cumulative Energy Demand comparing the two electricity mixes. It can be observed that while the Mexican mix has greater impact in the non-renewable, fossil; the renewable, biomass, and the renewable, water, the United States mix has the greatest impact, leading to having a greater single score overall. Figure 4-87 shows the characterization phase results and Figure 4-88 shows the single score results of the Cumulative Exergy Demand method that compared both electricity mixes. While the Mexican electricity mix has a greater impact in the non-renewable, fossil; the renewable, solar; the renewable, biomass; the renewable, potential and the non-renewable, minerals categories, once again the United States' electricity mix has the greatest overall impact. Thus, for several different EIA methods, the United States' electricity mix has a greater impact than the Mexican electricity mix.

The third sensitivity parameter evaluated for the subway was the vehicle's lifetime, which was increased from 33 years to 45 years of service. This sensitivity parameter was increased for a twofold reason, which did not include the fact that it was uncertain; on the contrary, the precise average train age was available from the STC-Metro transit authority (Public information request, November 2018). First, there was an interest in determining how an increased lifetime might reduce the environmental impacts in a per passenger-kilometer basis, thus providing Mexico City's authorities with a way to further assist in meeting lower emission thresholds. In the second place, since by the own admission of the transit authorities, most trains throughout the subway system in Mexico City are well beyond their expected lifetime, some of them still operating after 49 years of service, and the average train age of Line 3 being closer to 36 years, it was decided that an increased lifetime would more closely model the actual conditions on the ground.

Figure 4-89 shows the characterization phase results and Figure 4-90 presents the single score phase results of the BEES+ impact method applied to the increased lifetime train and the base case. As can be seen from these figures, it appears that there is no change in impact in any of the categories by an increased lifetime. Additionally, the impact of the train's manufacturing was in the order of 10^{-18}. Therefore, although it is reasonable to expect that this impact was spread and thus decreased over a longer lifetime, its magnitude was so small relative to the day-to-day electricity usage that it did not appear in the final results of this specific sensitivity scenario. However, the true, underlying cause that these figures are reading is that the lifetime VKT, for both the extended and the regular lifetime cases, is a function of the assumed daily and annual VKT. Hence, if these initial VKTs are the same for both scenarios, the final result will be the same, since normalizing the effects of the infrastructure modules by the respective lifetime VKT will yield the same result: we are in effect, multiplying and dividing by the same factors. However, another interesting conclusion that can be drawn from this sensitivity scenario is to ratify how small the contribution of the infrastructure modules becomes over the lifetime of the trains: if that were not so, this scenario would have detected a change in the impacts between the two different train lifetimes.

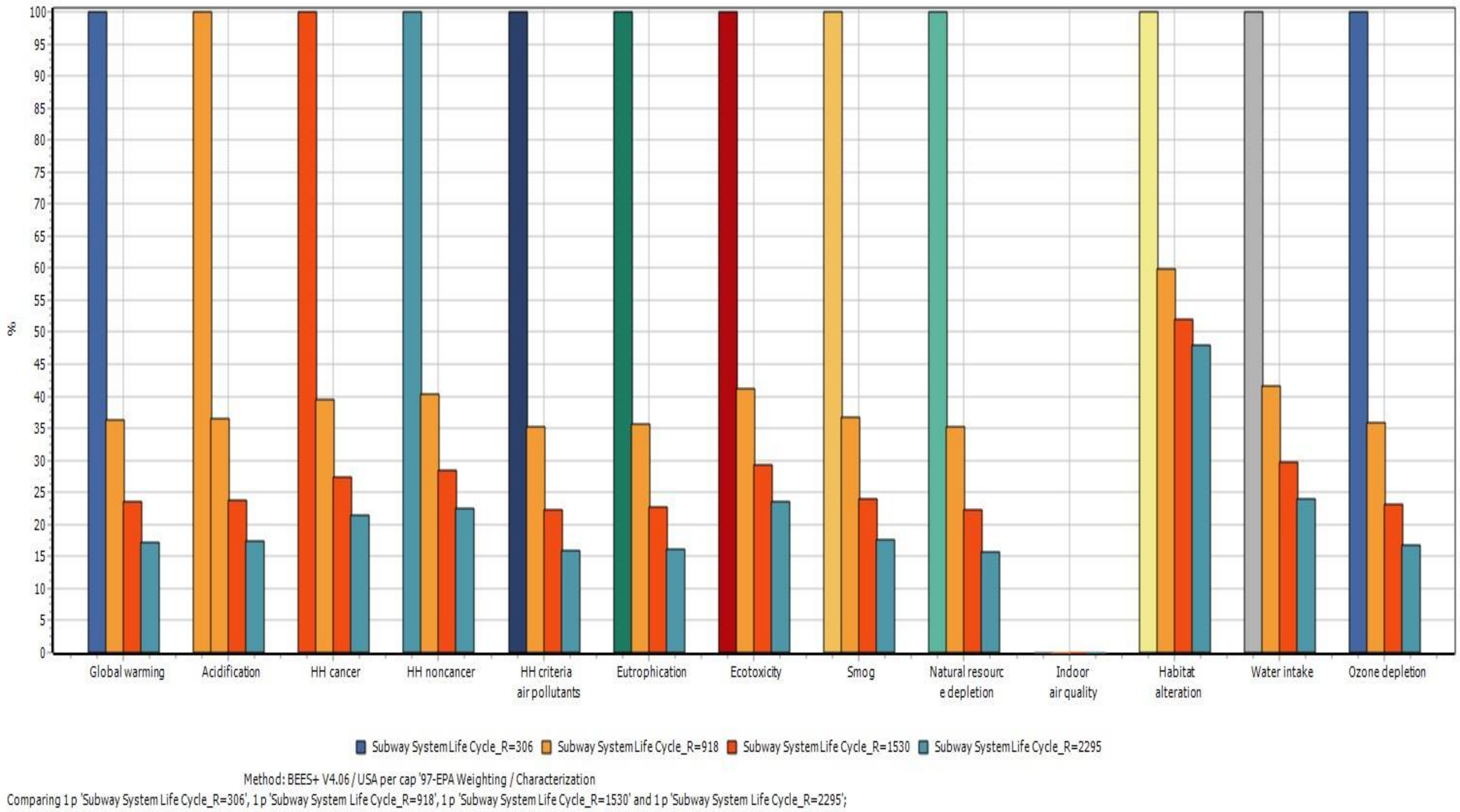


Figure 4-81. Subway, Sensitivity Analysis, Four Different Riderships. Characterization, BEES+ (Simapro software).

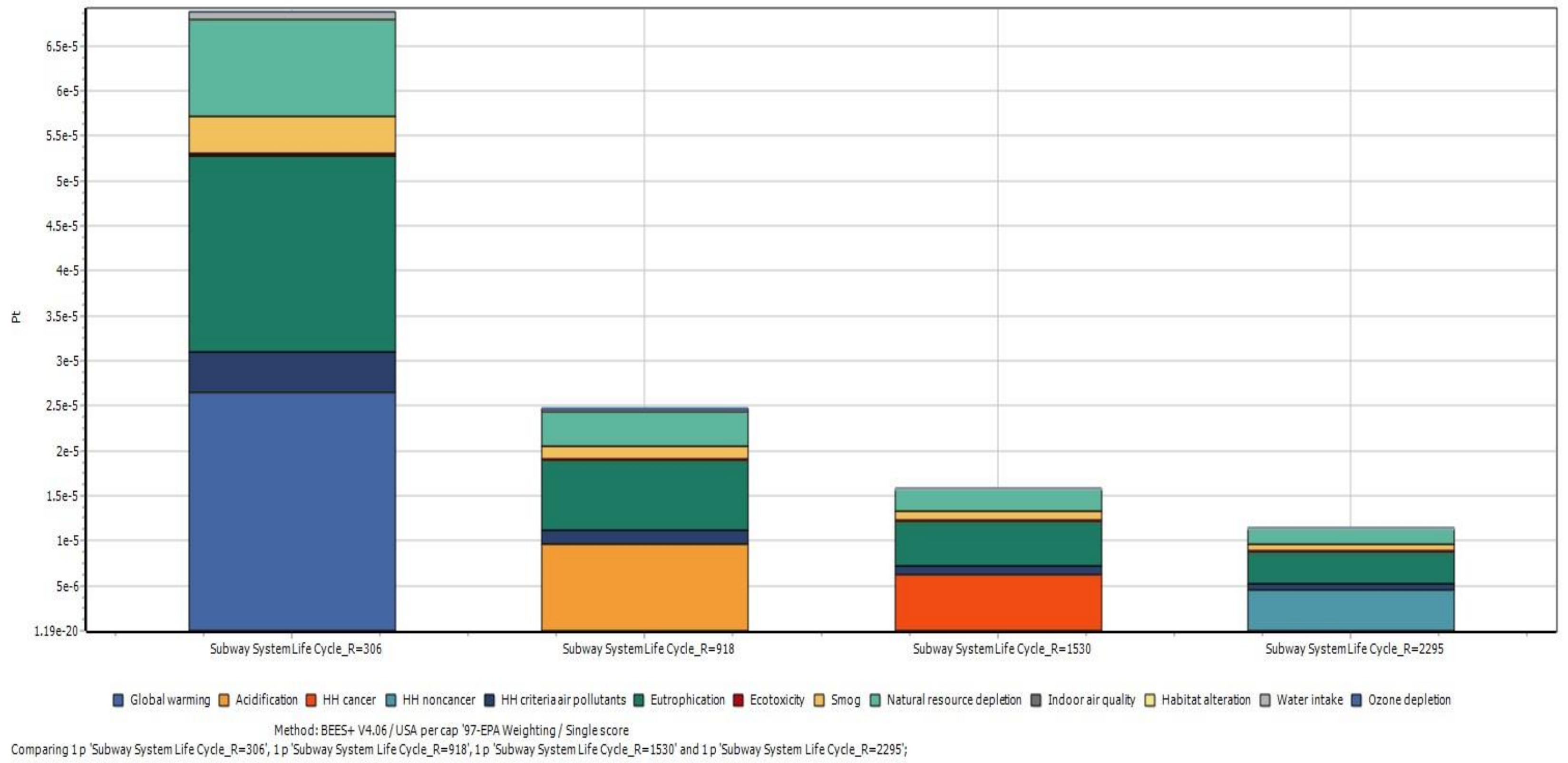


Figure 4-82. Subway, Sensitivity Analysis, Four Different Riderships. Single Score, BEES+ (Simapro software).

Table 4-20. Inventory Results for Sensitivity Analysis, Four Different Riderships, Subway: Greenhouse Gases and Criteria Air Pollutants.

Substance	Unit	Subway System Life Cycle R=306	Subway System Life Cycle R=918	Subway System Life Cycle R=1530	Subway System Life Cycle R=2295
Carbon dioxide, fossil	kg	0.0396	0.0143	0.00924	0.00671
Carbon monoxide, fossil	kg	2.12E-05	1.17E-05	9.83E-06	8.88E-06
Dinitrogen monoxide	kg	4.43E-06	1.50E-06	9.19E-07	6.26E-07
Hydrocarbons, aliphatic, alkanes, cyclic	kg	5.80E-09	5.62E-09	5.58E-09	5.56E-09
Hydrocarbons, aromatic	kg	4.51E-07	1.59E-07	1.01E-07	7.21E-08
Hydrocarbons, chlorinated	kg	2.86E-10	2.35E-10	2.24E-10	2.19E-10
Hydrocarbons, unspecified	kg	6.11E-10	3.91E-10	3.47E-10	3.25E-10
Lead	kg	9.59E-09	4.22E-09	3.14E-09	2.60E-09
Methane	kg	1.06E-07	3.55E-08	2.13E-08	1.42E-08
Nitrogen dioxide	kg	3.61E-07	1.20E-07	7.21E-08	4.81E-08
Nitrogen oxides	kg	7.82E-05	2.87E-05	1.88E-05	1.39E-05
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.44E-05	7.69E-06	6.35E-06	5.68E-06
Particulates, < 10 µm	kg	7.56E-10	2.52E-10	1.51E-10	1.01E-10
Particulates, < 2.5 µm	kg	7.41E-05	2.59E-05	1.62E-05	1.14E-05
Particulates, > 2.5 µm, and < 10 µm	kg	4.19E-05	1.45E-05	9.04E-06	6.31E-06
Sulfur dioxide	kg	0.000162	5.89E-05	3.82E-05	2.79E-05
Sulfur hexafluoride	kg	1.46E-08	4.96E-09	3.04E-09	2.08E-09
VOC, volatile organic compounds	kg	3.97E-10	1.32E-10	7.94E-11	5.30E-11

Table 4-21. Impact Categories for Different Riderships, Sensitivity Analysis for Subway.

Impact category	Unit	Subway System Life Cycle R=306	Subway System Life Cycle R=918	Subway System Life Cycle R=1530	Subway System Life Cycle R=2295
Total	Pt	6.88E-05	2.47E-05	1.59E-05	1.15E-05
Global warming	Pt	2.64E-05	9.58E-06	6.21E-06	4.52E-06
Acidification	Pt	7.36E-09	2.69E-09	1.75E-09	1.29E-09
HH cancer	Pt	1.41E-08	5.57E-09	3.87E-09	3.02E-09
HH noncancer	Pt	5.52E-09	2.23E-09	1.57E-09	1.24E-09
HH criteria air pollutants	Pt	4.46E-06	1.58E-06	9.98E-07	7.21E-07
Eutrophication	Pt	2.19E-05	7.77E-06	4.96E-06	3.55E-06
Ecotoxicity	Pt	3.19E-07	1.31E-07	9.36E-08	7.49E-08
Smog	Pt	4.05E-06	1.49E-06	9.74E-07	7.18E-07
Natural resource depletion	Pt	1.08E-05	3.79E-06	2.40E-06	1.70E-06
Indoor air quality	Pt	0	0	0	0
Habitat alteration	Pt	4.42E-13	2.65-13	2.30E-13	2.12E-13
Water intake	Pt	7.86E-07	3.26E-07	2.34E-07	1.88E-07
Ozone depletion	Pt	3.69E-08	1.32E-08	8.52E-09	6.15E-09

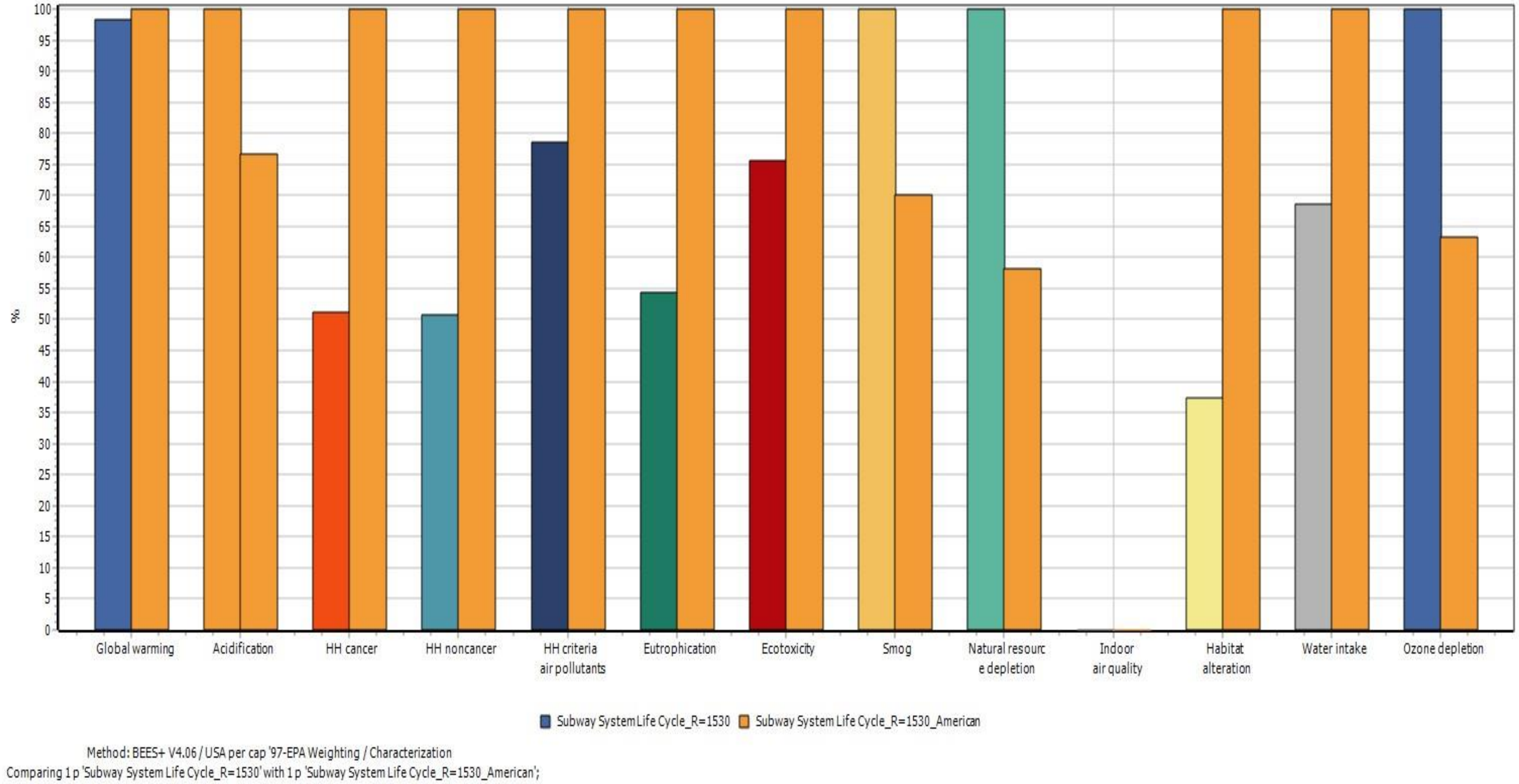


Figure 4-83. Subway, Sensitivity Analysis, Electricity Mix. Characterization, BEES+ (Simapro software).

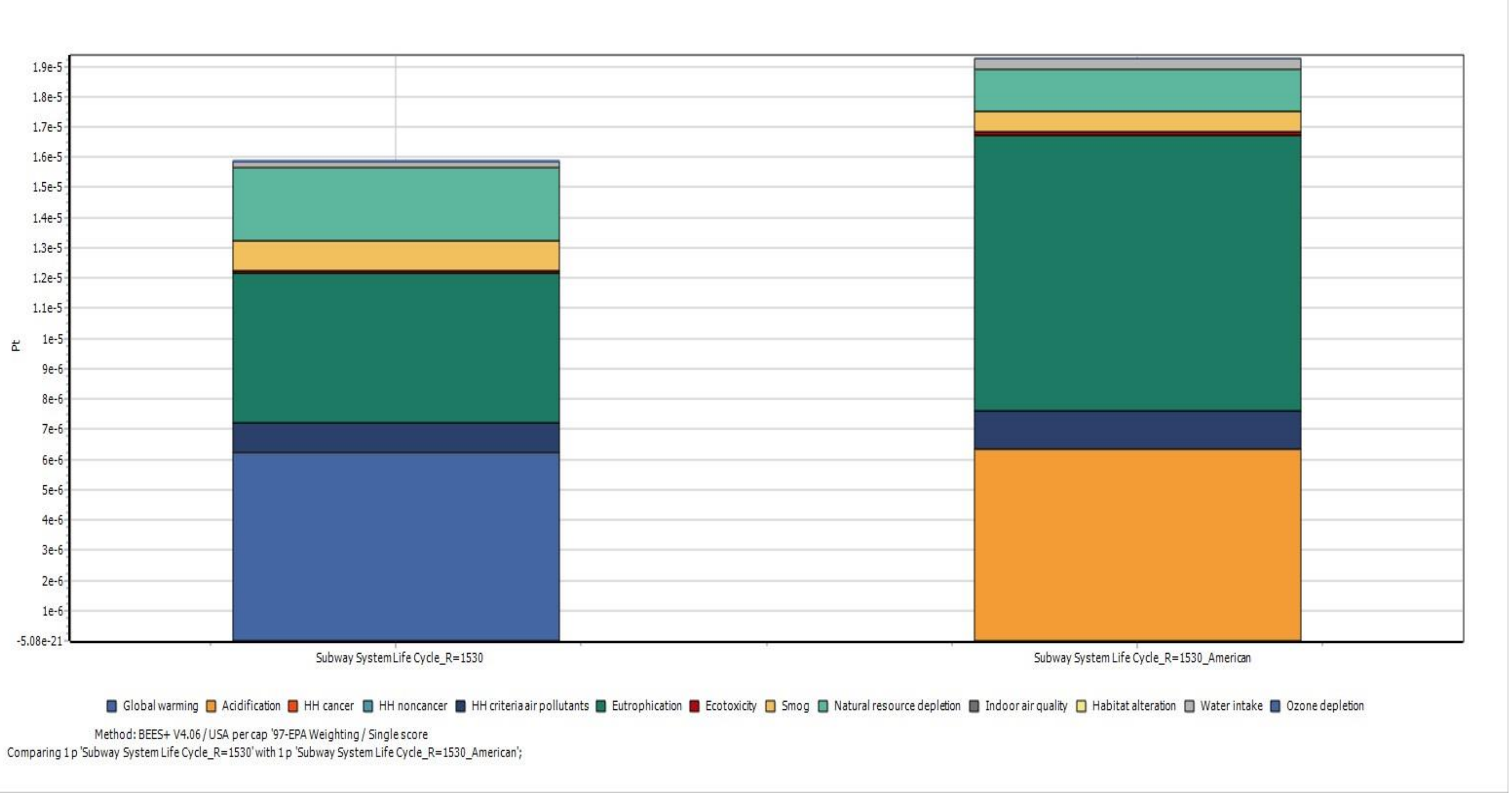


Figure 4-84. Subway, Sensitivity Analysis, Electricity Mix. Single Score, BEES+ (Simapro software).

Table 4-22. *Impact Category Results for Sensitivity Analysis, Electricity Mix (Simapro software).*

Impact category	Unit	Subway System Life Cycle_R=1530	Subway System Life Cycle_R=1530_American
Total	Pt	1.59E-05	1.93E-05
Global warming	Pt	6.21E-06	6.32E-06
Acidification	Pt	1.75E-09	1.34E-09
HH cancer	Pt	3.87E-09	7.56E-09
HH noncancer	Pt	1.57E-09	3.09E-09
HH criteria air pollutants	Pt	9.98E-07	1.27E-06
Eutrophication	Pt	4.96E-06	9.10E-06
Ecotoxicity	Pt	9.36E-08	1.24E-07
Smog	Pt	9.74E-07	6.82E-07
Natural resource depletion	Pt	2.40E-06	1.39E-06
Indoor air quality	Pt	0	0
Habitat alteration	Pt	2.30E-13	6.14E-13
Water intake	Pt	2.34E-07	3.42E-07
Ozone depletion	Pt	8.52E-09	5.39E-09

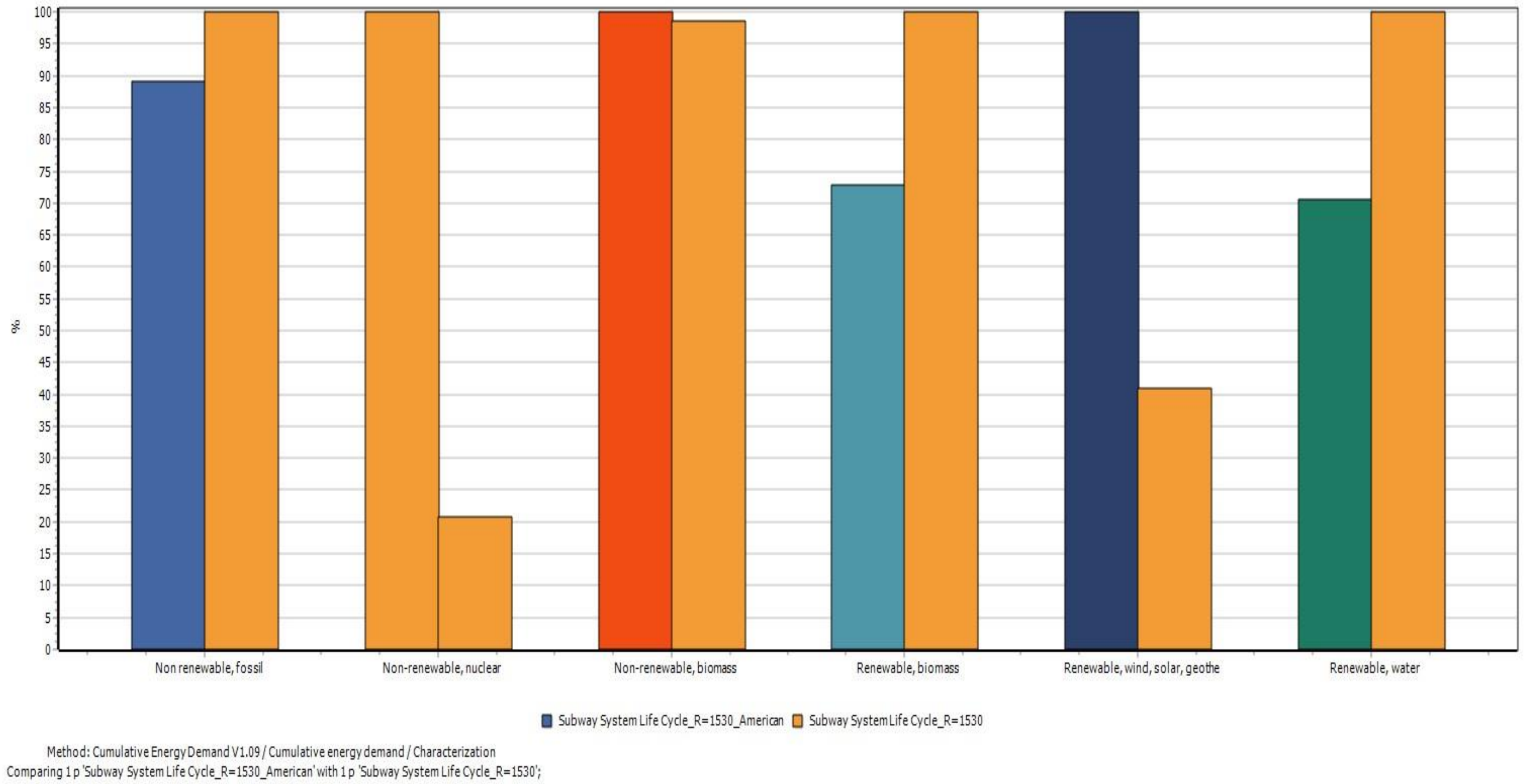


Figure 4-85. Subway, Sensitivity Analysis. Different Electricity Mix. Characterization, Cumulative Energy Demand (Simapro software)

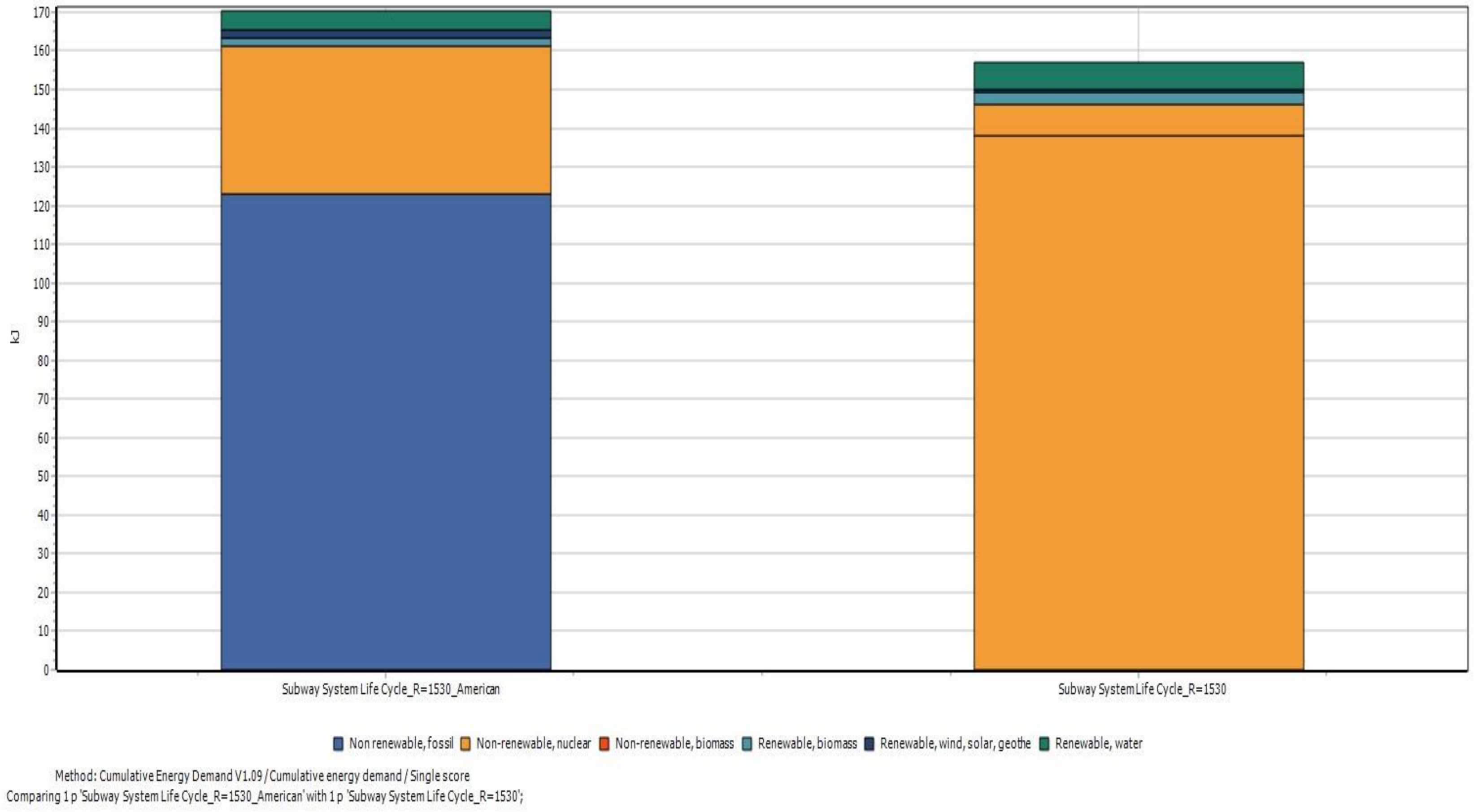


Figure 4-86. Subway, Sensitivity Analysis, Different Electricity Mix. Single Score, Cumulative Energy Demand (Simapro software).

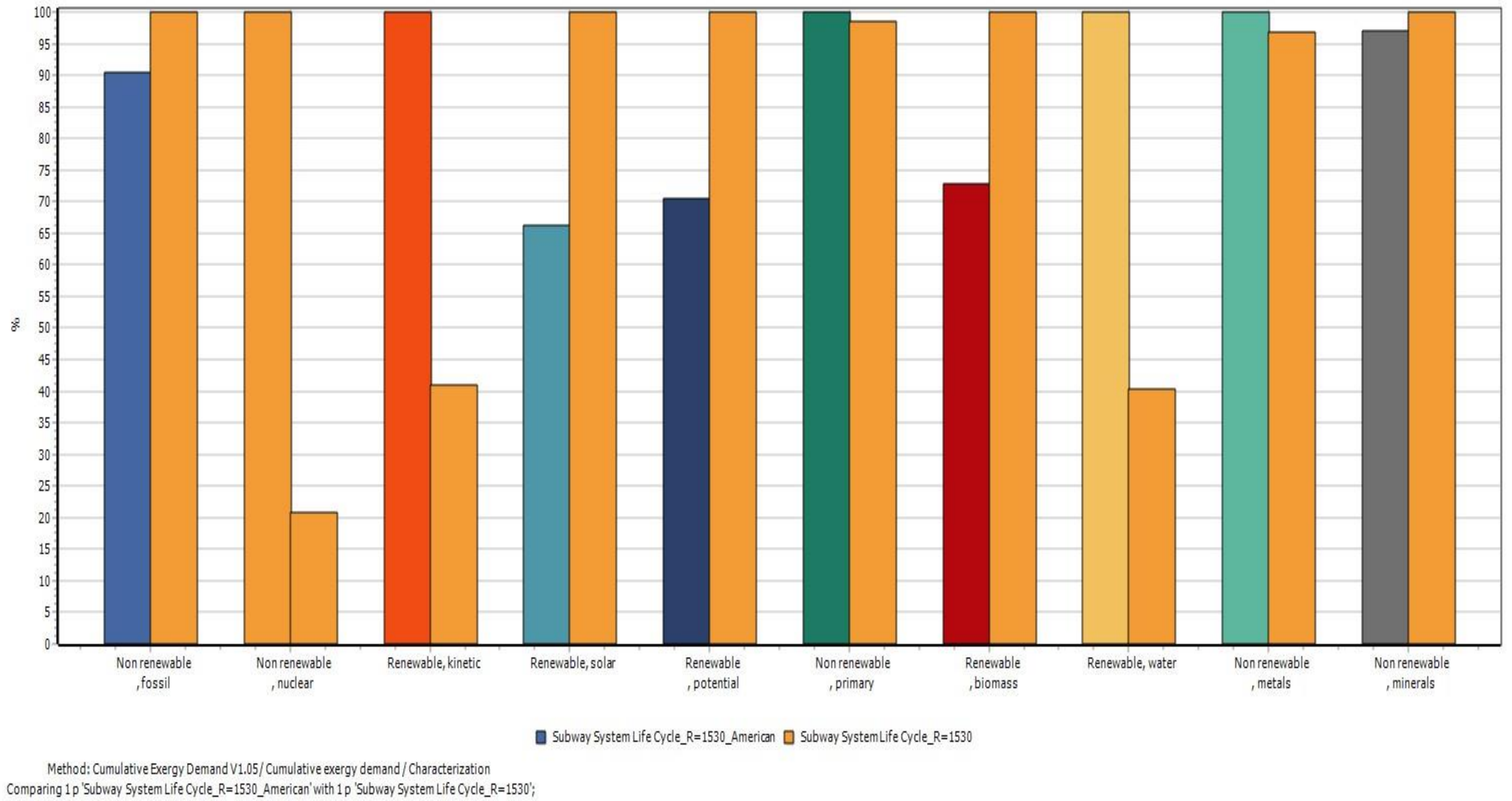


Figure 4-87. Subway, Sensitivity Analysis, Different Electricity Mix. Characterization, Cumulative Exergy Demand (Simapro software).

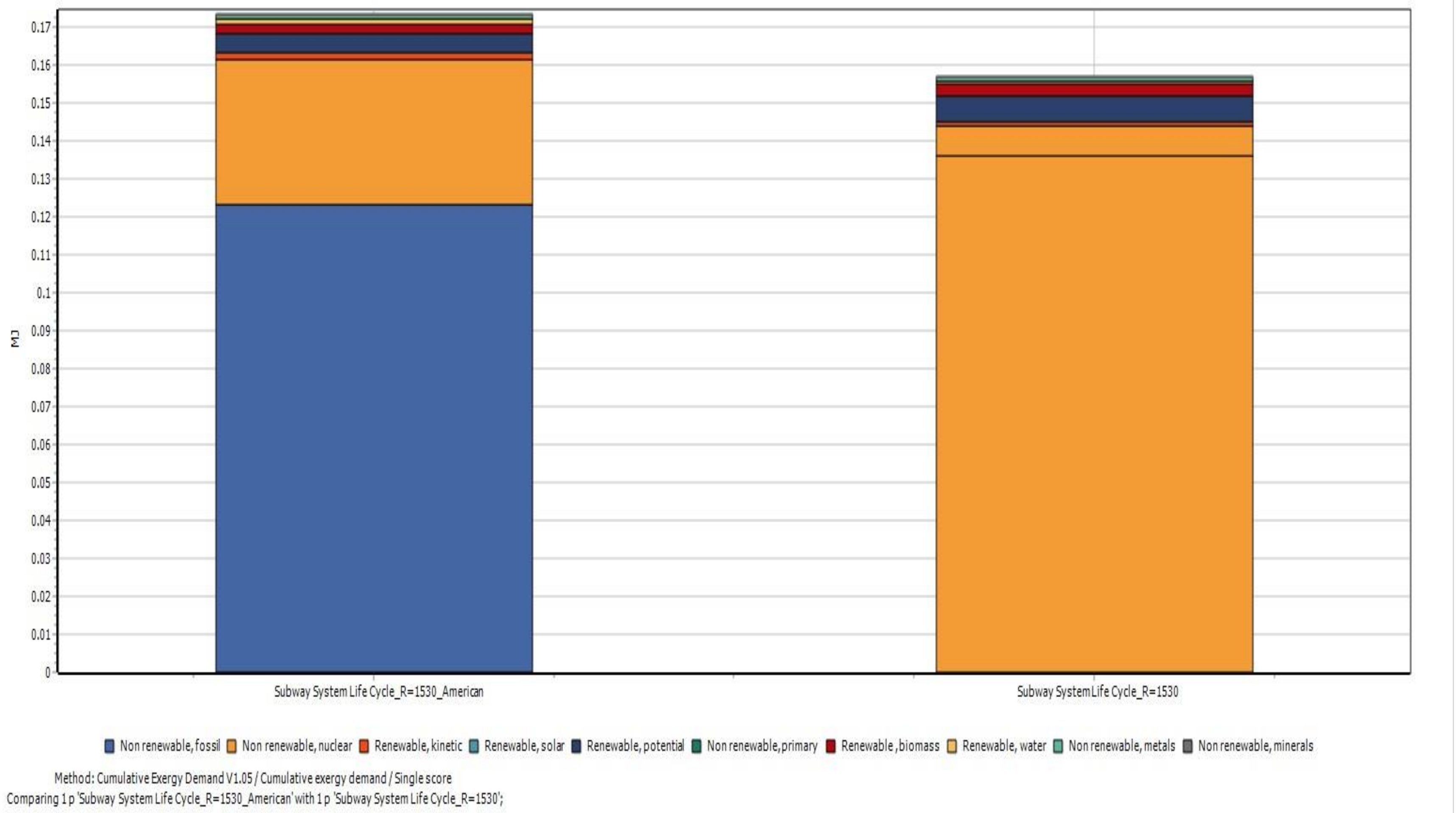
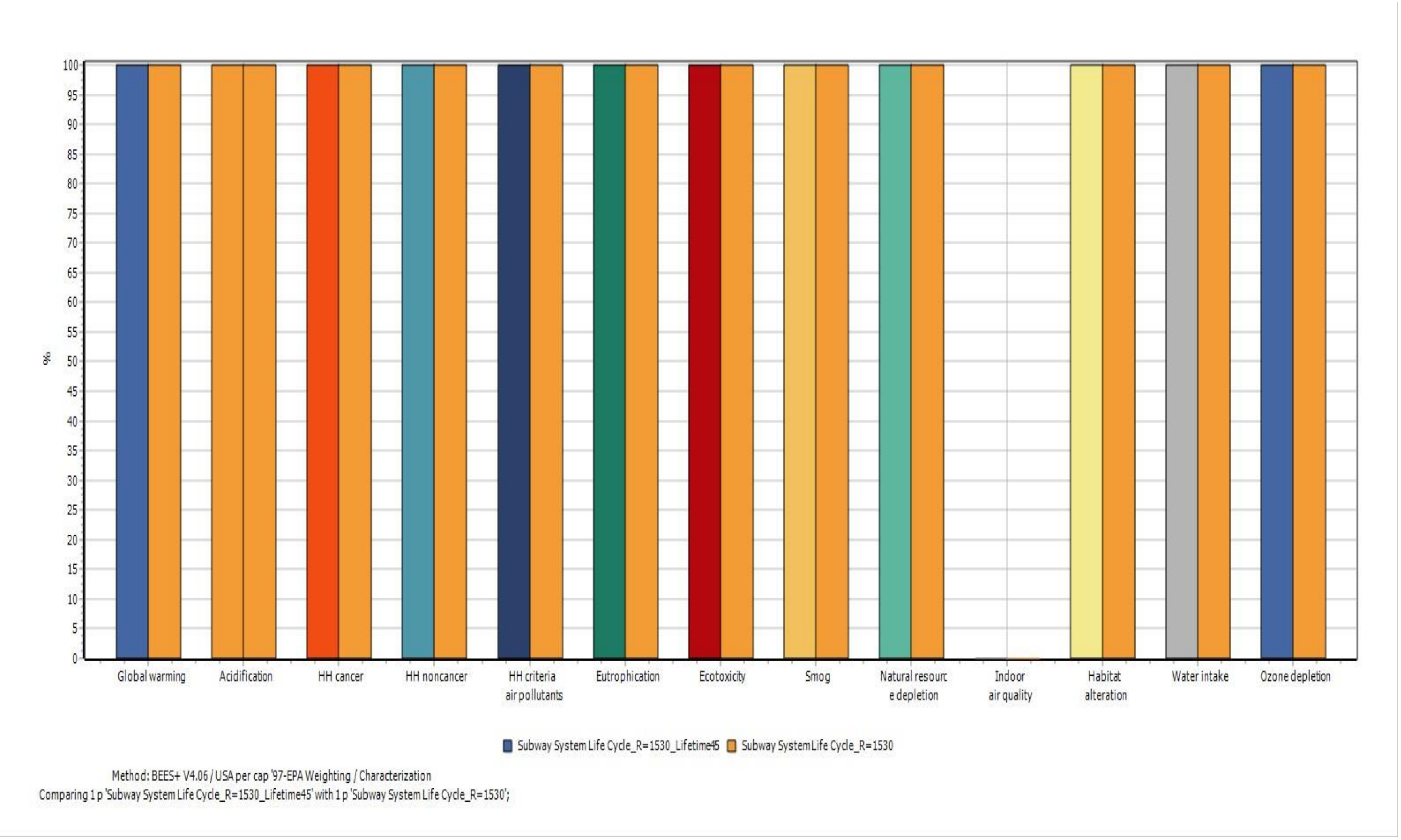


Figure 4-88. Subway, Sensitivity Analysis, Different Electricity Mix. Single Score, Cumulative Exergy Demand (Simapro software).



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Characterization
Comparing 1 p 'Subway System Life Cycle_R=1530_Lifetime45' with 1 p 'Subway System Life Cycle_R=1530';

Figure 4-89. Subway, Sensitivity Analysis, Different Vehicle Lifetimes, Characterization, BEES+ (Simapro software)

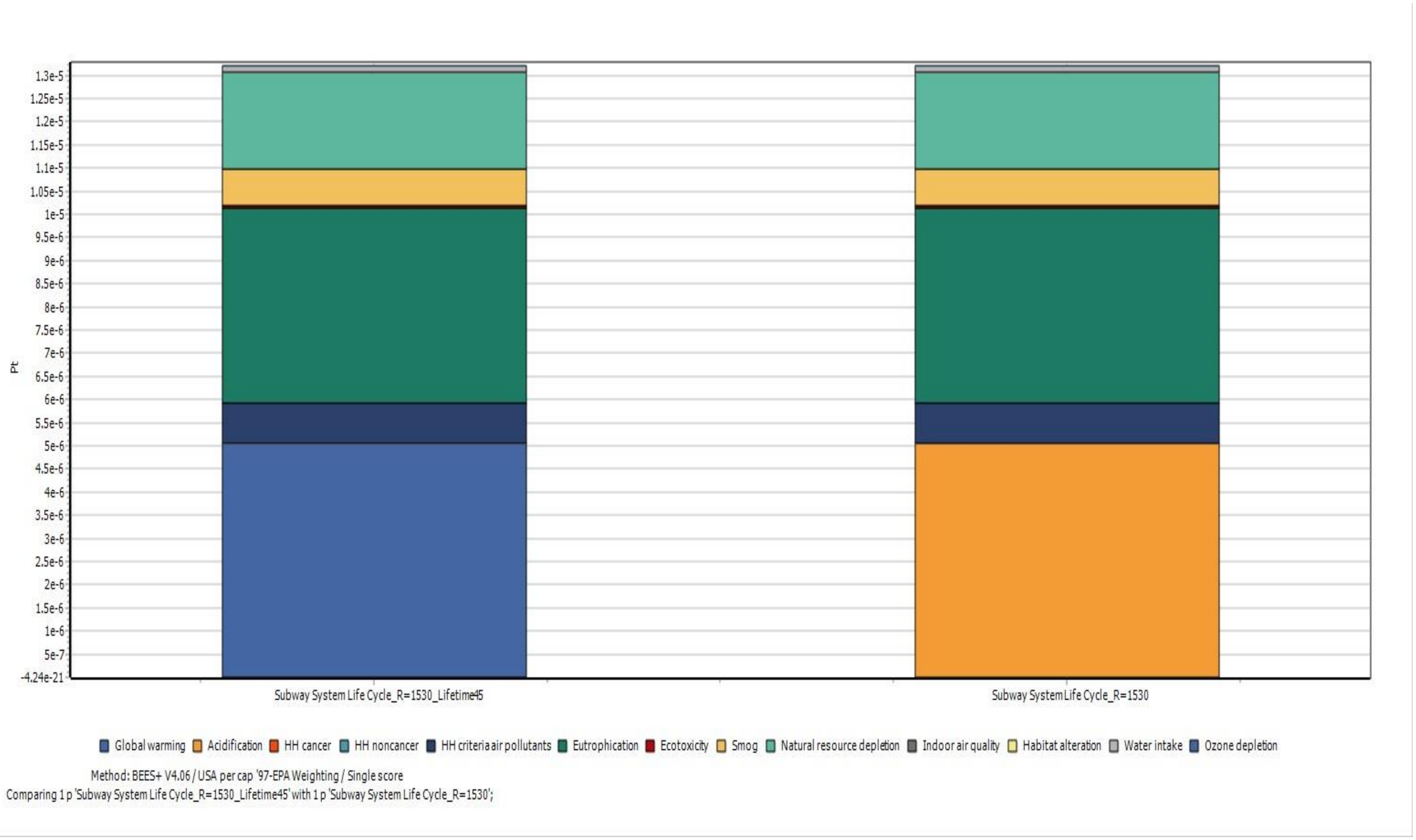


Figure 4-90. Subway, Sensitivity Analysis, Different Vehicle Lifetimes, Single Score, BEES+ (Simapro software).

4.7 Summary Comparison of the Three Transportation Modes

To provide better clarity on the final results for the LCAs of the three modes, Table 4-23 presents a summary, at the inventory level, and in a per passenger-kilometer basis, of the greenhouse gases and criteria air pollutants for each of the base cases of the three transportation modes analyzed in this dissertation. It can be observed that in all cases the greatest inventory corresponds to the car, and in most cases, it is followed by the BRT, with the last place corresponding to the subway. Exceptions to this are ozone and sulfur hexafluoride, where the BRT has lower figures than the subway. This is naturally offset by all other air pollutants, where the lowest generated emissions are those of the subway, in some cases, such as VOCs, by a dramatic seven orders of magnitude difference relative to the car.

Table 4-23. Summary Inventory of GHG and CAP Airborne Pollutants for the Base Cases of the Three Transportation Modes.

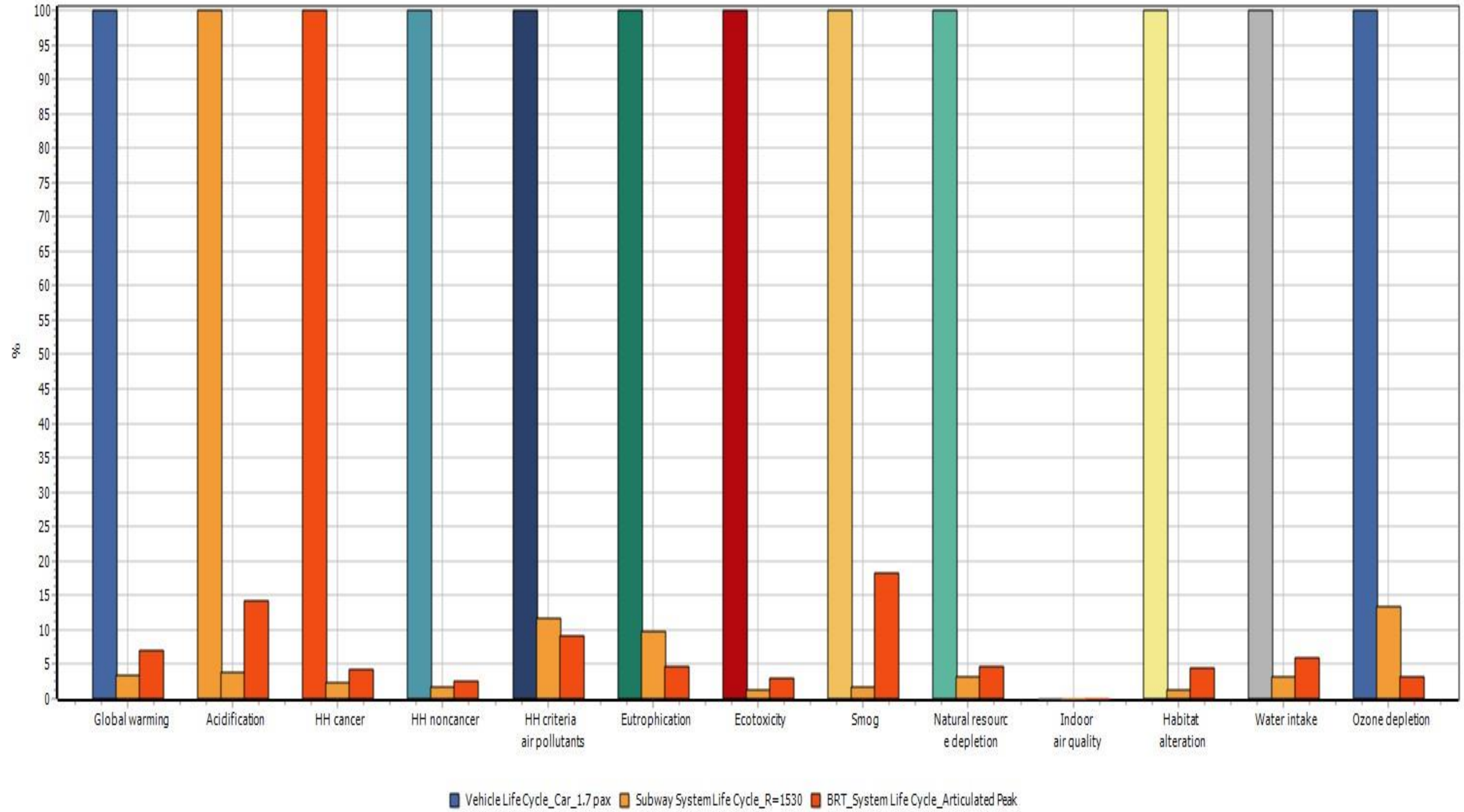
Substance	Unit	Vehicle Life Cycle_Car_1.7 pax	BRT_System Life Cycle_Articulated Peak	Subway System Life Cycle_R=1530
Carbon dioxide, fossil	kg	0.2208	0.0156	0.0076
Carbon monoxide, fossil	kg	0.0033	7.99E-05	2.82E-06
Dinitrogen monoxide	kg	9.32E-06	2.09E-07	8.78E-07
Hydrocarbons, aromatic	kg	7.61E-07	1.91E-08	8.73E-08
Hydrocarbons, chlorinated	kg	3.31E-08	6.76E-09	1.52E-11
Hydrocarbons, unspecified	kg	2.02E-04	4.71E-06	6.29E-11
Lead	kg	9.60E-08	4.82E-09	1.60E-09
Methane, fossil	kg	1.46E-04	6.84E-06	8.88E-06
Nitrogen dioxide	kg	2.99E-05	6.51E-06	6.83E-08
Nitrogen oxides	kg	6.76E-04	1.49E-04	1.48E-05
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.84E-04	7.18E-06	2.01E-06
Ozone	kg	2.84E-07	9.20E-09	5.73E-08
Particulates, < 10 µm	kg	1.20E-05	4.35E-06	1.43E-10
Particulates, < 2.5 µm	kg	9.22E-05	7.29E-06	1.45E-05
Particulates, > 2.5 µm, and < 10 µm	kg	3.65E-05	2.84E-06	8.19E-06
Sulfur dioxide	kg	3.44E-04	2.04E-05	3.10E-05
Sulfur hexafluoride	kg	8.69E-09	2.79E-10	2.88E-09
VOC, volatile organic compounds	kg	2.17E-04	6.84E-06	7.52E-11

Additionally, applying the BEES+ Impact Assessment method to the base case of each transportation mode produces the results shown in Figure 4-91 for the characterization phase and in Figure 4-92 for the single score phase. These figures present a graphic representation of the magnitude of the impacts for each system.

Moreover, a summary comparison for the base cases of the three transportation modes was also run using the Cumulative Energy Demand method and the Cumulative Exergy Demand method. Figure 4-93 shows the results of this comparison for the characterization phase of the Cumulative Energy Demand and Figure 4-94 for the single score phase of the same method.

Figure 4-95 shows the results of comparing the base cases of the three modes using the Cumulative Exergy Demand method, at the characterization phase, and Figure 4-96 shows these results at the single score phase of the same method. Once again, these figures aid in understanding at a single glance the very significant impacts among the three systems.

Finally, a sensitivity analysis across both mass transit modes, the bus and the subway, was run to ascertain whether the subway is always the mode with the least impacts, or the bus becomes the mode with the least impacts in some scenarios. Thus, the subway with the low ridership of 918 passengers/train was compared against both the Articulated, Peak Bus (160 passengers) and the Bi-Articulated, Peak Bus (240 passengers), which are both the high ridership cases for the bus. Table 4-24 presents the inventory of Greenhouse Gases and Criteria Air Pollutants for this comparison, and Figure 4-97 shows the single score phase of assessing these scenarios with the BEES+ method. While the subway, even with a low ridership, maintains its advantage over the Peak Articulated bus, this is not so in the case of the Peak, Bi-articulated bus, which in this scenario becomes the mode with the lowest impacts. This result once again underscores the sensitivity of this methodology and of all transportation modes to ridership, and suggests that when planning a public transportation option, it behooves policy makers to strive to have the best available data on ridership, so as to make the best possible decision on which transportation mode to invest, or to encourage.



Method: BEES+ V4.06 / USA per cap '97-EPA Weighting / Characterization

Comparing 1 p 'Vehicle Life Cycle_Car_1.7 pax', 1 p 'Subway System Life Cycle_R=1530' and 1 p 'BRT_System Life Cycle_Articulated Peak';

Figure 4-91. Summary Comparison, Three Modes of Transportation, Characterization, BEES+ (Simapro software).

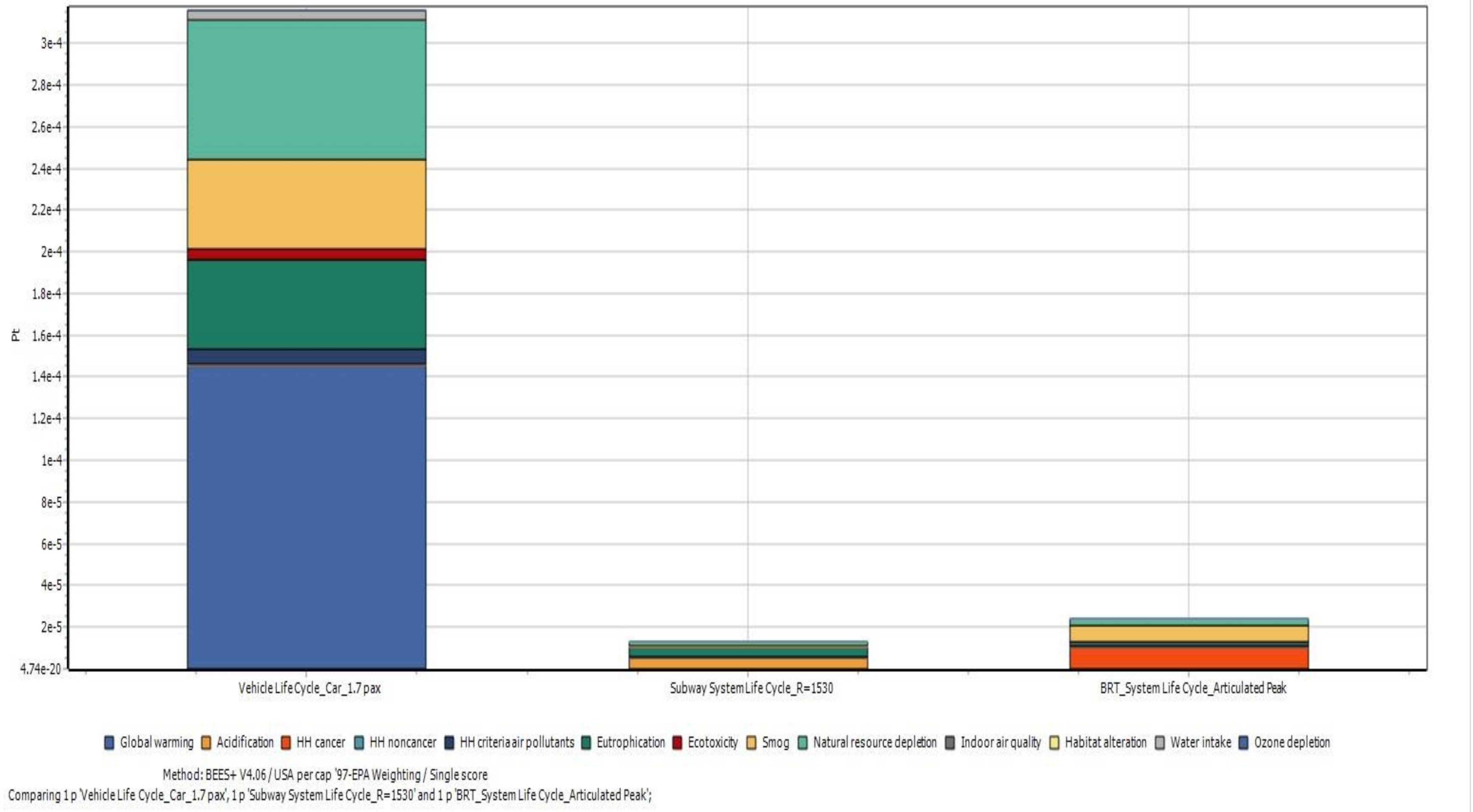


Figure 4-92. Summary Comparison, Three Transportation Modes, Single Score, BEES+ (Simapro software).

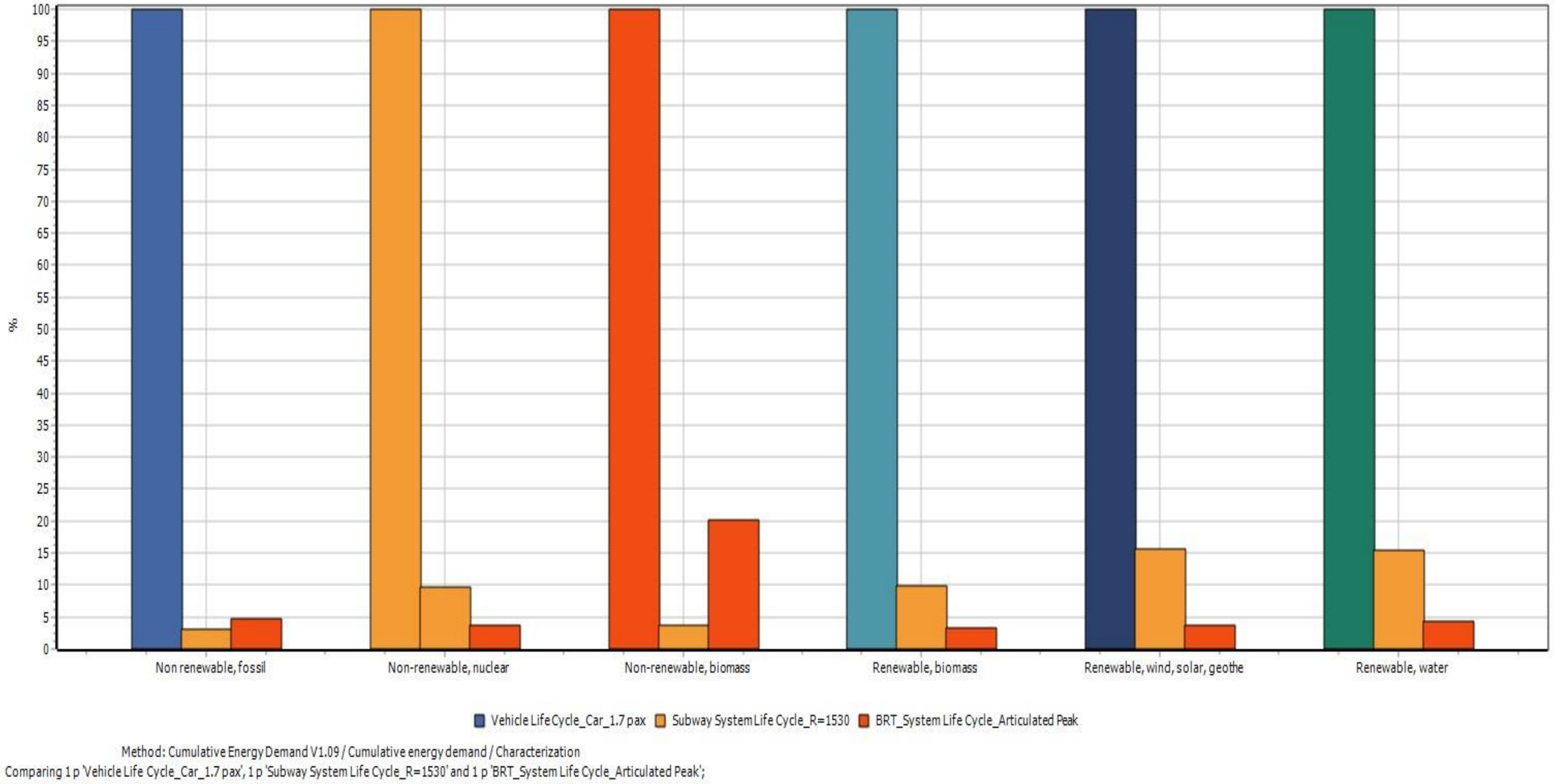


Figure 4-93. Summary Comparison, Three Transportation Modes, Characterization, Cumulative Energy Demand (Simapro software).

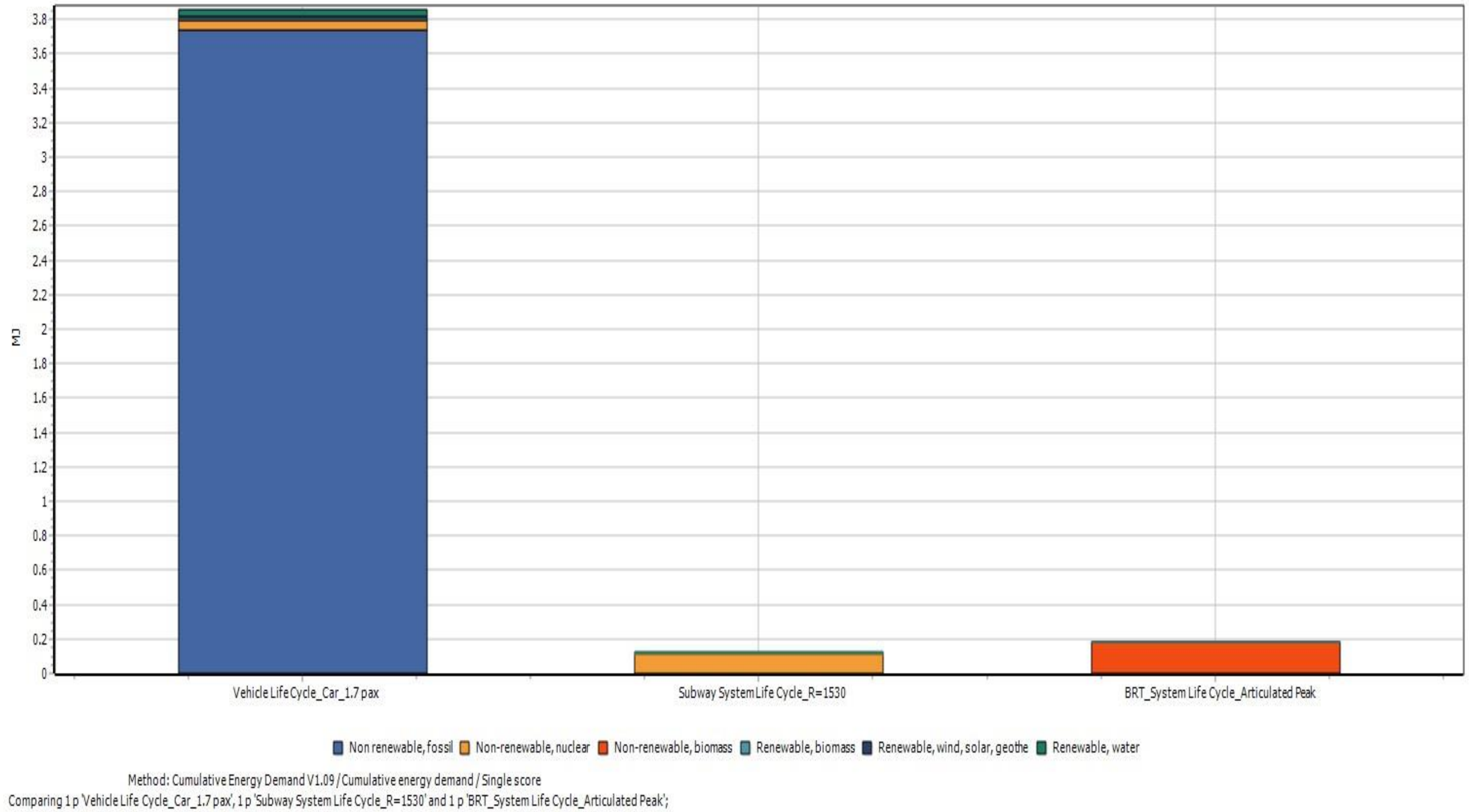


Figure 4-94. Summary Comparison, Three Transportation Modes, Single Score, Cumulative Energy Demand (Simapro software).

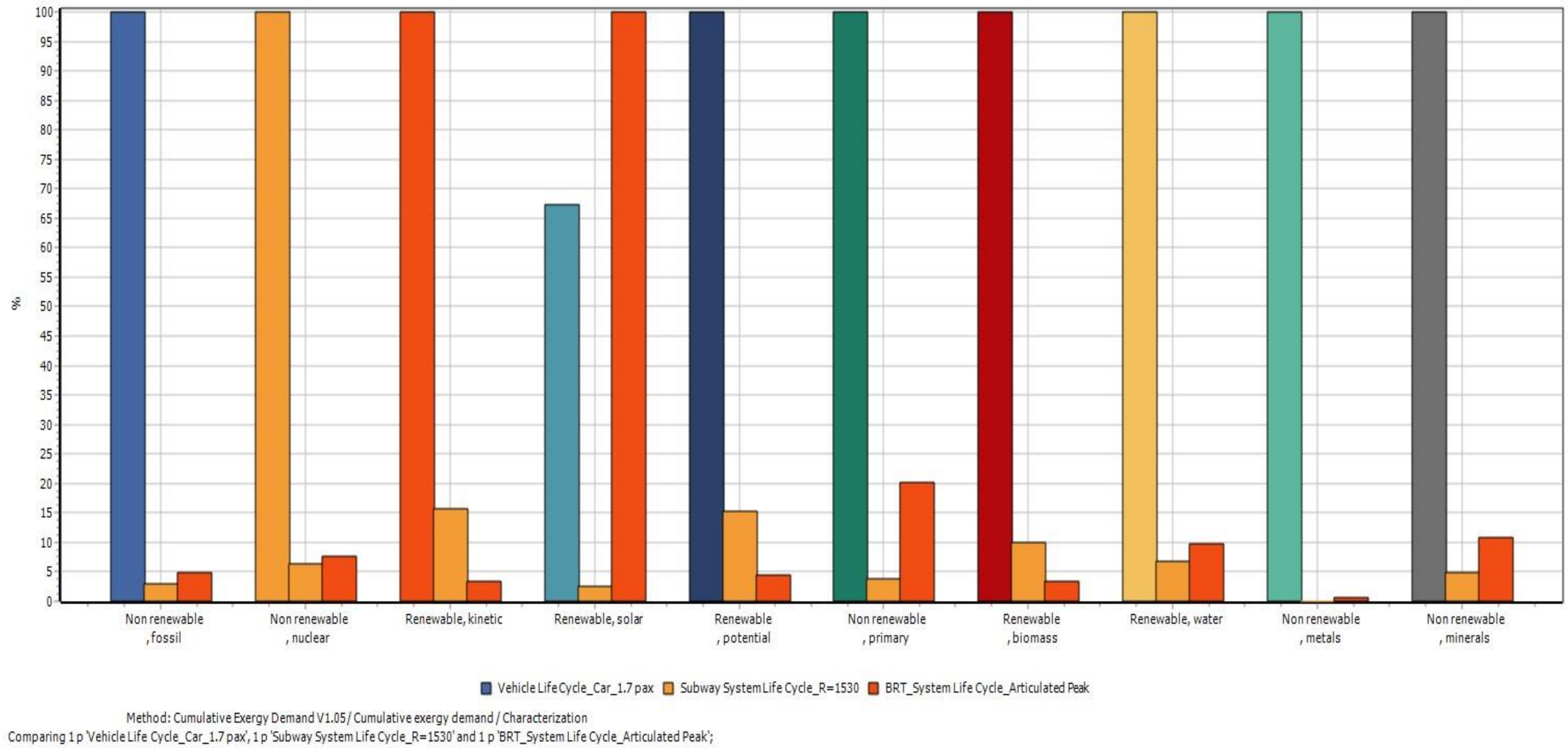


Figure 4-95. Summary Comparison, Three Transportation Modes, Characterization, Cumulative Exergy Demand (Simapro software).

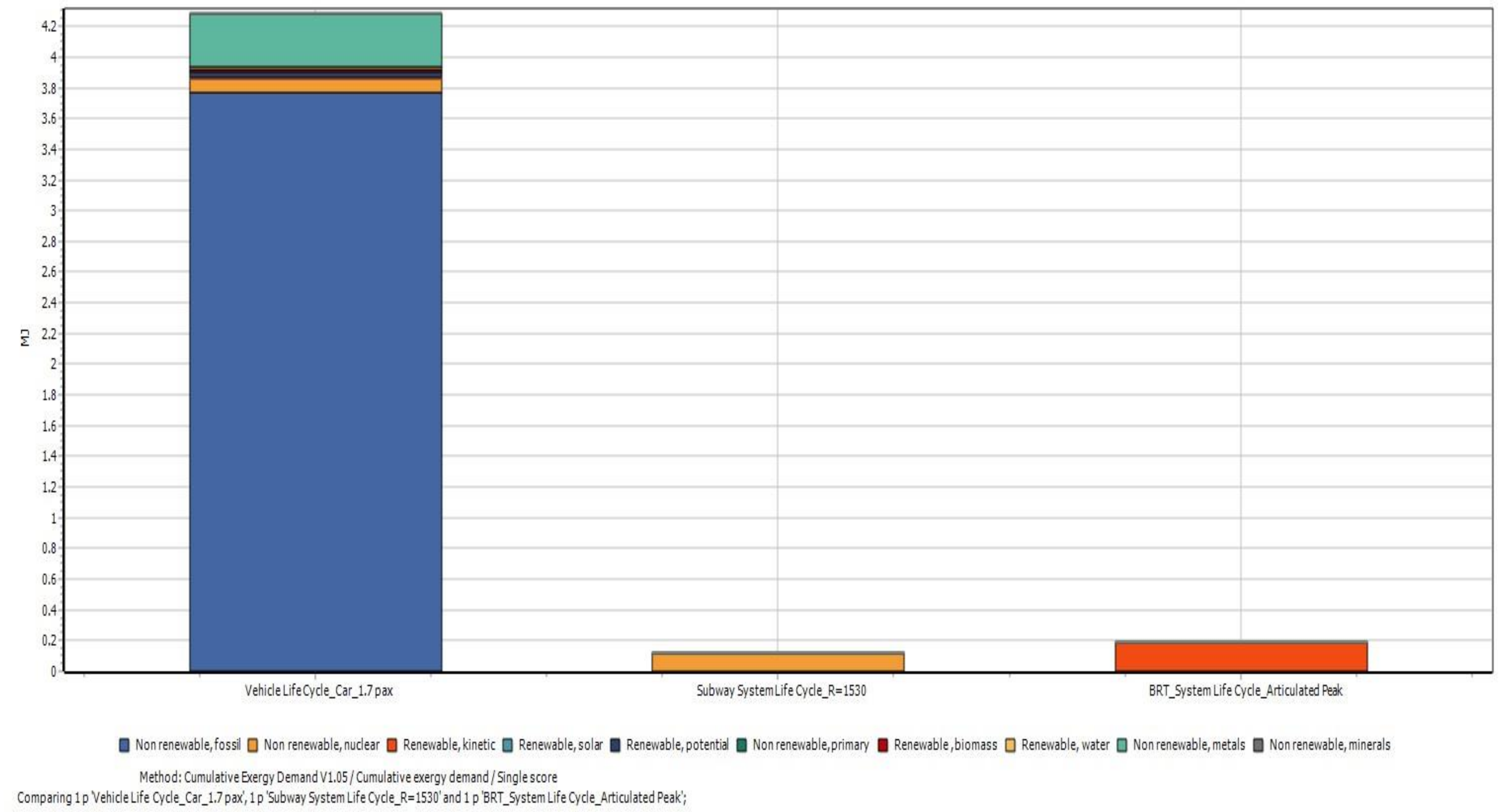


Figure 4-96. Summary Comparison, Three Transportation Modes, Single Score, Cumulative Exergy Demand (Simapro software).

Table 4-24. Inventory of GHG and CAP for Sensitivity Analysis between Low Ridership, Subway and Peak Ridership, Bus

Substance	Unit	Subway System Life Cycle_R=918	BRT_System Life Cycle_Articulated Peak	BRT_System Life Cycle_Bi Articulated Peak
Carbon dioxide, fossil	kg	0.0126	0.0156	0.0122
Carbon monoxide, fossil	kg	4.71E-06	7.99E-05	6.02E-05
Dinitrogen monoxide	kg	1.46E-06	2.09E-07	1.42E-07
Hydrocarbons, aromatic	kg	1.46E-07	1.91E-08	1.41E-08
Hydrocarbons, chlorinated	kg	2.53E-11	6.76E-09	4.78E-09
Hydrocarbons, unspecified	kg	1.05E-10	4.71E-06	4.24E-06
Lead	kg	2.67E-09	4.82E-09	3.83E-09
Methane, fossil	kg	1.48E-05	6.84E-06	4.94E-06
Nitrogen dioxide	kg	1.14E-07	6.51E-06	5.85E-06
Nitrogen oxides	kg	2.47E-05	0.000149	0.000115
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.35E-06	7.18E-06	4.79E-06
Ozone	kg	9.55E-08	9.20E-09	6.43E-09
Particulates, < 10 µm	kg	2.38E-10	4.35E-06	3.91E-06
Particulates, < 2.5 µm	kg	2.41E-05	7.29E-06	5.95E-06
Particulates, > 2.5 µm, and < 10 µm	kg	1.37E-05	2.84E-06	1.92E-06
Sulfur dioxide	kg	5.17E-05	2.04E-05	1.36E-05
Sulfur hexafluoride	kg	4.81E-09	2.78E-10	1.96E-10
VOC, volatile organic compounds	kg	1.25E-10	6.84E-06	5.56E-06

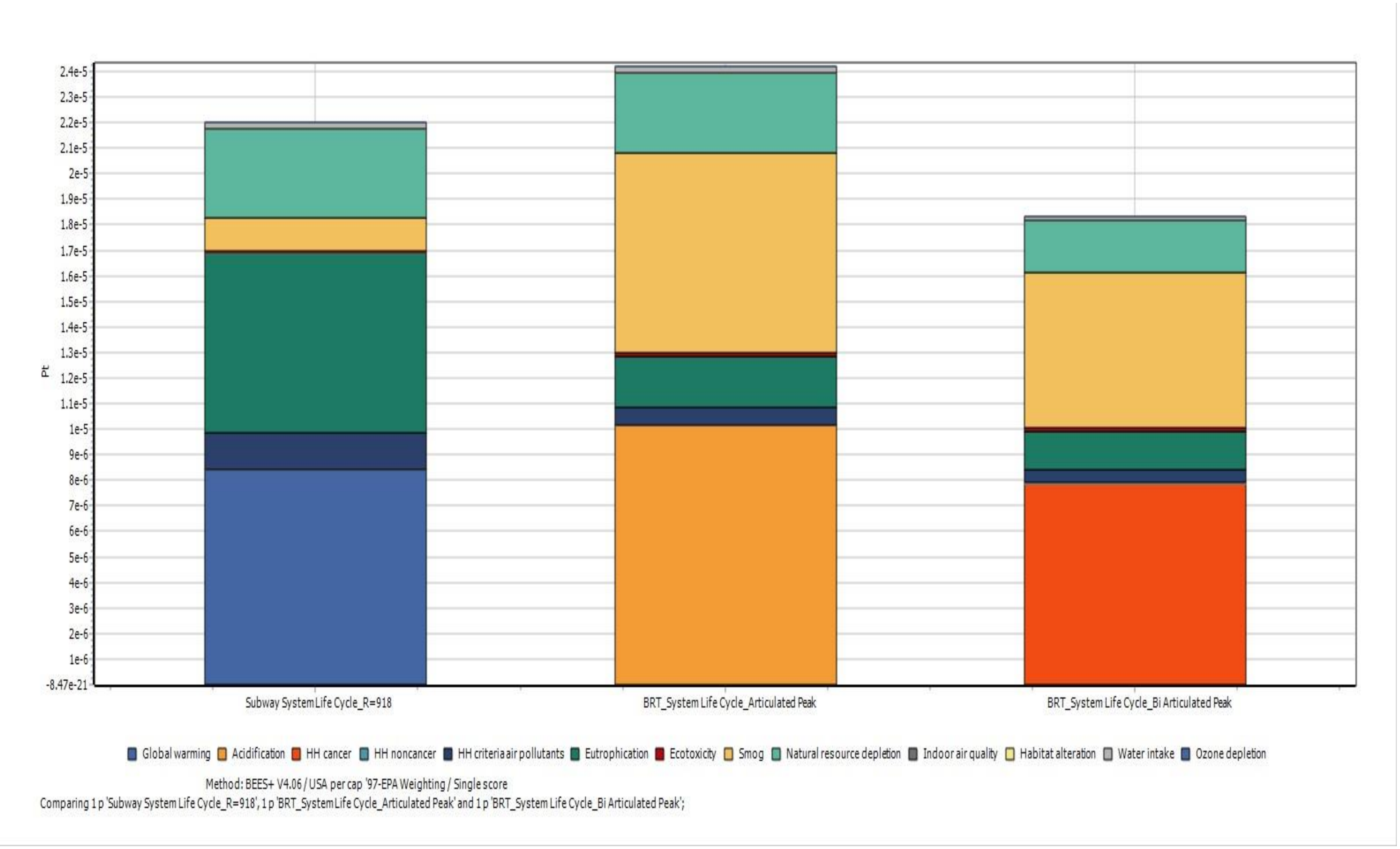


Figure 4-97. Subway Low Ridership versus Peak Ridership for BRT Comparison, Single Score, BEES+ (Simapro software).

4.8 Possible Underestimation of Infrastructure Impacts on the Subway

It is duly noted that due to the following reasons, the impacts of the infrastructure subsystem for the subway may have been underestimated in the present study. First, there were no blueprints nor architectural renderings available, so while the dimensions for the railway, the platforms, and the general length of the stations and depots were accurate, based as they were on the technical specification manuals for the Mexico City subway, and on similar information from other subway systems, generalizations on the number of walls, offices, surfaces and volumes of construction may have been underestimated, at least as compared to what occurred for the calculation of the BRT system. Second, the machinery types are limited in Simapro. Case in point, there is no record for any type of Tunnel Boring Machine in Simapro, and while the record called "Excavation, Mining, {GLO}" was in fact used to simulate the excavation for the subway, it is not clear if this is an open-pit or a tunnel-based record. Furthermore, there is no tunneling construction record in Simapro, neither for the mining industry nor for any related sector, such as the oil and gas industry. Also, there are no records related to the maintenance and repair of tunnels. However, it is well known that for the case study of Mexico City, there exists an intensive and continuous program of maintenance for the subway tunnels. Thus, it was unfortunate that none of this was taken into account for this system's calculations. Therefore, while the materials and processes for the railway tracks are considered quite accurate, as are the calculations for the stations and depots, those related to the tunnels, and their entire life cycle, are likely underestimated.

Table 4-25 lists the known Simapro limitations, particularly those that may have led to underestimating the impacts of the subway's infrastructure subsystem.

Table 4-25. List of known Simapro limitations for this study.

Limited machinery types available: no grader nor scraper
Limited excavators and excavation technology available
No tunnel boring machine available
Unclear if “Excavation, mining {GLO}” record refers to open pit or tunnel
No tunneling construction record, no tunneling maintenance option available

Chapter 5

CONCLUSIONS, FINDINGS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions and Findings

5.1.1 Conclusions Regarding the Development of TransportLifeCAMM

The spreadsheet-based model TransportLifeCAMM was developed, which allows engineers/government employees in the US and Mexico to compare life cycle environmental impacts from automobile, bus, and/or subway transportation systems in their urban areas. For each of the 3 transportation modes, TransportLifeCAMM includes vehicles, fuel, and infrastructure (e.g. roadway, railway, stations, and depots). The user inputs values of readily available parameters such as average bus ridership, average car occupancy, number of depots, number of stations, length of roadway or railway kilometers built for the transportation mode, and TransportLifeCAMM outputs impacts customized to the transportation system in that urban area.

5.1.2 Conclusions and Findings for the BRT

The vehicle (bus) subsystem was the greatest contributor to the inventory for all criteria pollutants and greenhouse gases. Furthermore, it was also always the greatest contributor to the impacts, when evaluated by all impact assessment methods (BEES+, Traci, Impact 2002+, CED and CExD).

A finding for this LCA, in the sense of an unexpected result, was that the second place among the contributors to environmental impacts varied, depending on the method utilized. While Impact 2002+, CED, CExD and BEES+ assigned the second place to the station module, Traci considered the road module as the second-place contributor to impact. This finding highlights the importance of taking care in choosing the impact assessment method that best fits the purposes of the LCA, and of course also underlines the difference between endpoint and midpoint methods.

5.1.3 Conclusions and Findings for the Private Car

For the private car, the vehicle subsystem was also the greatest contributor to both the inventory and the impacts, across all categories and regardless of the impact assessment method utilized. As mentioned in Section 4.7, the car is the most environmentally burdensome system analyzed in this dissertation, as initially expected and in line also with scientific literature.

It was also interesting to ratify, through the results of this study, previous claims that infrastructure contributions can increase contaminants very significantly, when studied in an LCA framework. While Chester *et al* (2010) had found a 1,400% increase in $PM_{2.5}$ relative to a system that did not consider infrastructure, in this dissertation a sevenfold increase was found. While not as dramatic, it nevertheless underscores the importance of including infrastructure to obtain a truly comprehensive, LCA-oriented perspective of the system under study.

A finding for the car system was the fact that the Exergetic Life Cycle Assessment correctly identified the work performed by car’s battery as exergy. This result was probably made possible by the greater granularity and the level of detail that was used in the simulation of the car’s maintenance. Nevertheless, it was a welcome finding in that it confirmed the usefulness of exergy, and of the exergetic life-cycle assessment, in identifying available work (exergy) from a system.

5.1.4 Conclusions and Finding for the Subway

The main conclusion for the subway system is the acceptance of the initial hypothesis, and the rejection of the null hypothesis, that the subway, while not a “zero-emissions” transportation mode, does represent the least environmentally burdensome transportation alternative, among the three modes studied herein, for urban passenger transportation.

Another important conclusion for the subway was the confirmation of how dependent its environmental profile (i.e., its final output) is to the composition of the electricity mix. Since it was also found that the emissions from the subway are almost entirely dependent on the electricity used for its operation, with much less significant contributions from the infrastructure than for the onroad modes, it must be pointed out that in order to increase the efficiency of the subway system, and further decrease its environmental impact, authorities would do well to find ways to decrease the transmission losses of electricity throughout the system. Eventually, the most significant way in which to improve the environmental profile of the subway is to decrease the emissions associated with the local electricity mix.

A finding for the subway system was to observe how much the impact, measured in terms of grams per passenger-kilometer, is decreased, compared to other modes of transportation, not only by the ridership, i.e., the number of passengers, but even before that, in the previous calculation step in this methodology, by the lifetime VKT, or the sizable number of kilometers travelled over the train's lifetime. Ridership was expected to mark a difference, relative to other modes; the effects of lifetime VKT were an unexpected result.

In a three-way sensitivity analysis among the three transportation modes that evaluated both environmental impacts (with the BEES+ method), the Cumulative Energy Demand and the Cumulative Exergy Demand, it was confirmed that the heavy metro or subway has the least environmental impact and energy consumption, in a per passenger-kilometer basis. This is mostly the result of an increased ridership, with the subway's trains ability to transport a number of passengers, over their lifetime, that is at least two orders of magnitude above that of buses and cars. One of the findings of this research is that the increased lifetime performance, i.e., the greater number of kilometers travelled by each vehicle (car, bus, train) over their respective lifetimes, is also one of the factors that contributes to the subway's lesser environmental impact over the other two transportation modes analyzed herein.

In a two-way sensitivity analysis between the two mass transit modes, the bus and the subway, the low ridership case for the subway (918 passengers) was compared against both cases of "peak" buses for the BRT: the articulated bus carrying 160 passengers, and the bi-articulated bus with 240 passengers. Results showed that while the subway maintained its environmental advantage, in impacts measured in a per passenger-kilometer basis, over the articulated bus, it did not do so when compared to the bi-articulated bus, which performed marginally better than the subway. This result confirms the sensitivity of this methodology and of all transportation modes to ridership, and suggests that when planning a public transportation option, it behooves policy makers to strive to have the best available data on ridership, so as to make the best possible decision regarding on which transportation mode to invest, or to encourage.

5.2 Recommendations for Future Research

Several research areas or topics can be further explored after this dissertation. Among them, the following are listed.

1. Further LCA research into construction methods for the subway. As reviewed in Section 3.4.2, there are at least five distinct construction techniques for the subway, which can be built superficially, in elevated viaducts, or underground. Even for the construction of the underground subway, there exists substantial difference between the "cut and cover" methods, the slurry walls, the "drill and blast" methods, and the construction with tunnel boring machines. Interestingly, these latter techniques are essentially mining methods, and further research into them, from a Life Cycle Assessment perspective, would probably yield useful applications to better estimate their environmental impacts not only for transportation purposes but for the construction and mining industries as well. A quick bibliographic review into this topic shows that at the present,

the application of Life Cycle Assessment in the mining industry is still limited. Hence, there exists ample opportunity for research in this area.

2. Research into each of the transportation modes can be expanded to include vehicles with alternative fuels. In the case of the car, the LCA analysis of a diesel-powered car would probably not add much, since these cars are limited in number, both in Mexico and in the United States. However, research and eventual inclusion into the TransportLifeCAMM model of a hybrid car would provide LCA practitioners and public policy makers with more elements to reach a better decision, regarding different transportation modes, and the best among them under particular circumstances. Similarly, eventually analyzing an electric car from an LCA perspective, and including it into TransportLifeCAMM, would be a valuable exercise to see whether the electricity's advantage over fossil fuels, from an environmental standpoint, extends from the subway to the car, and if it does, in what measure.
3. Similarly, LCA research into Compressed Natural Gas (CNG) buses for the BRT, hybrid buses, and eventually, buses combusting biodiesel would also provide better elements for decision making, and contribute to the current understanding of these systems at the academic level as well.
4. Further research into other transportation modes using the methodology employed in this dissertation, and the inclusion of the results from that research into TransportLifeCAMM would also make it a more robust model, and contribute to the LCA in Transportation area simultaneously. Particularly, research into Light Rail, with its ridership lower than the heavy subway but higher than a bus, as a midpoint solution between these two ridership thresholds, merits further attention.
5. Regarding the accuracy of the emission factors used for the energy (fuel) subsystems of the onroad modes, it must be recalled that the emission factors used for this dissertation were those present in the USLCI's records, which is tantamount to using the EPA's MOVES 2010b's

emission factors directly. The Mexican Institute of Ecology and Climate Change (INECC) has recently commissioned the elaboration of emission factors tailored to Mexican cars and buses, meteorology, and activity levels, that are obtained from running MOVES-Mexico. Indeed, while the development of MOVES-Mexico is a joint international effort, undertaken by the same developers of the EPA's MOVES, and the results of the 2013 national inventory obtained with this program were published in 2014, the simulations for the 2016 inventory are currently underway. The emission factors from MOVES-Mexico are slated to be available (upon special request) during the third week of December, 2018. Naturally, replacing the USLCI's emission factors used in this dissertation with these soon-to-be-available Mexican emission factors will increase the accuracy of TransportLifeCAMM's results. Likewise, the eventual inclusion of Canadian emission factors where appropriate would make the applicability of TransportLifeCAMM both more international in scope and more accurate in its representation of local reality and conditions.

6. Examine the environmental impacts of increased ridership on a given transportation mode relative to economic costs, changes in land use and access to the mode.
7. A future version of TransportLifeCAMM would ideally allow the user to vary the depths of the pavement's layers, to further customize the model to local conditions and systems.
8. Further research and sensitivity analyses for the different weighting sets available within BEES+. Although the present study was not concerned with that aspect, further study would probably be useful in uncovering contributors or hidden opportunities for improvement within each system.
9. Conduct an expanded sensitivity analysis, developing a systematic way to identify the greatest or more significant contributors to impacts.

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Biographical Information

Alma Angelica Hernandez Ruiz has earned a doctorate in civil engineering (environmental engineering), a masters of engineering in civil engineering (environmental engineering) and a bachelor's of science in chemical engineering. Dr. Hernandez-Ruiz started her career working for the Procter and Gamble Co., in Cincinnati, Ohio, as an international intern. She was later hired by Procter and Gamble de México and worked at their Research and Development Department of the Paper Products division, before being awarded the Fulbright-García Robles US-Mexico scholarship for doctorates in Science and Engineering.

Dr. Hernandez-Ruiz has worked for several research teams at the Institute of Engineering of the National Autonomous University of Mexico (UNAM) and of the School of Chemistry of the same university. Her research projects have included analyzing the influence of guiding curves in the optimal management of the Grijalva river hydropower system and several applied cases of Geographic Information Systems (GIS) to rainfall-runoff modeling in the Water Resources engineering area. Additionally, Dr. Hernandez-Ruiz was in charge of the creation of the GIS (database and system) and of the national map, at the 1:250,000 scale, for the National Wetlands Inventory, an initiative undertaken by the Mexican National Water Commission (CONAGUA) by President Calderon's directive. Dr. Hernandez-Ruiz was also part of the team from the National University (UNAM) that carried out the environmental impact assessment prior to the planned 14.5 billion U.S. dollar expansion of the largest Mexican refinery, located at Tula, Hidalgo.

Dr. Hernandez-Ruiz looks forward to applying her educational credentials and experience to the many opportunities for problem solving that lay at the vast interface of chemical, environmental, civil and transportation engineering. Additionally, her skills set and character make her a valuable asset both in the consulting industry, in mentoring and in other positions where critical decision-making is required.